A Housing Energy Management Program Report

Energy
Ontario

INDOOR AIR QUALITY
20 EXISTING HOMES

Project undertaken jointly by the Ontario Ministries of Municipal Affairs and Housing and Energy under the Housing Energy Management Program (H.E.M.P.).

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by

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1.0 SUMMARY

1.1 Introduction

Some activities inside homes produce air contaminants. The activities of smoking, cooking, eating or cleaning can introduce many contaminants into the air of homes. Even the introduction of new materials can produce increased levels of air contamination. The common contaminants found in homes are carbon monoxide and carbon dioxide, oxides of nitrogen, both nitric oxide and nitrogen dioxide, radon and its daughter products and formaldehyde.

All these pollutants will continue to accumulate in the house if it is not ventilated. Normal ventilation due to the exhausting of combustion products from furnaces or fireplaces and the operation of exhaust fans in kitchens and bathrooms creates a negative pressure in the house which promotes the infiltration of fresh air. In addition to mechanical exhaust systems the house itself can act as a chimney with fresh air being infiltrated in the basement and lower levels of the house and stale air being exfiltrated in the upper areas of the house. Such exfiltration of warm, moist air from the upper areas of houses can lead to severe structural problems. This is particuarly exaggerated in well insulated homes if precautions are not taken to reduce the leakage rate. To overcome such problems, and to reduce energy consumption, it is becoming more common to have a house sealed. This sealing process is referred to as "air sealing". This is a systematic, comprehensive approach to stopping up the cracks and holes which allow for uncontrolled infiltration and exfiltration of air and moisture in homes. Air sealing measures are primarily undertaken on the inner or warm surface of the structure. As can be appreciated, this air sealing will tend to lower the natural air exchange rates or ventilation rates in the house. If the ventilation rate is reduced, contaminants can build up in the house. Residents might notice more persistent odours and increased occurrences of condensation on cold surfaces.

Complaints related to moisture problems in a small number of the 65 houses sealed under a demonstration program prompted the Ontario Ministry of Municipal Affairs and Housing to initiate a study of 20 air sealed (weatherized) demonstration homes in the Cambridge, Ontario area. The Ontario Ministry of Municipal Affairs and Housing contracted IEC Beak Consultants Ltd., with funds provided by the Ministry of Energy

under the Home Energy Management Program (H.E.M.P.), a project designed to test indoor air quality (IAQ) in the houses. Work was conducted during late March and April 1983.

1.2 Methods

The intent of the project was to quickly measure air quality conditions in the homes to ascertain if any problems existed. Measurements of the common contaminants, carbon monoxide, carbon dioxide, oxides of nitrogen, radon and its daughter products, and formaldehyde, were undertaken in each home. Average concentration of these contaminants in the air was measured. Additional work was carried out to measure the air exchange rates, the relative humidity and temperature and to ascertain the operation of combustion appliances in the various homes. Attempts were also made to gather information on the lifestyle of the residents to ascertain if this affected the indoor air quality.

Testing commenced in late March 1983. A field technician set up the appropriate number of pumps to take three interior samples of each of the contaminants - carbon dioxide, carbon monoxide and nitrogen oxides. One exterior sample for these contaminants was also taken. Sampling for these contaminants normally took two to four hours.

Passive formaldehyde dosimeters were installed in two locations in the house and one location outside. The formaldehyde devices were left in the houses for seven days.

One radon "track etch" device was placed in the basement of each home. External radon levels were measured at ten locations only. The radon devices were left for a period of between 20 and 44 days.

After commencing the sampling, the field technician assisted the home owner in completing the questionnaire that had been designed specifically for the project. This uniform approach reduced the bias typically found in survey data while maximizing the data recovery.

An inspection of the house was carried out. During this inspection, relative humidities using wet and dry bulb temperatures, were measured in various areas of the house.

Approximately halfway through the visit, samples of sulphur hexafluoride (SF_6) were injected into the air of the house to enable an air exchange rate to be calculated. Samples of the house air were removed at various intervals for the next two hours so that the change in concentration of SF_6 could be measured over each time interval.

At the conclusion of all the sampling programs the technician removed the sampling devices, and stored them for transport to the laboratory where they were analysed. Results of the analysis and the field data were used for interpretation purposes.

A select number of homes were subsequently tested for combustion air supply. This involved monitoring the furnace flue conditions (carbon dioxide concentration, stack draft pressure) under various ventilation scenarios.

With the exception of radon, there are currently no residential indoor air quality standards. It is thus not possible to say if the short term monitoring results from this study are above or below accepted levels. It is possible to use the ambient air quality levels which are legislated by the Ontario Government, the Industrial Hygiene Standards as enforced by the Ontario Ministry of Labour or reported health effects to indicate if recorded levels are within reasonable limits. A combination of these approaches were followed to define levels of acceptable indoor air quality for this study. Comments on the moisture levels in the homes are related to normally accepted values for this parameter. The operation of the various combustion devices was checked to see if it was satisfactory and the measurements were compared to normally accepted performance standards.

1.3 Results

The level of acceptable air contamination was developed for the purpose of this study. This "action" level was derived by a consideration of ambient, industrial hygiene and health effects information. These levels tend to be conservative as explained in detail in the text. Based upon the levels established in this study, the results of the measurements in each house could thus be compared. The results of the sampling programs showed that

a total of 36 measurements exceeded the various action levels selected. A total of 300 readings were made and thus the exceedances account for 12% of the total readings.

Distribution analyses were used to examine the relationship between levels of contaminants in the various houses. The results of the distribution analysis are shown in Table 1-1. The probability analysis provides a valuable first step in developing an appreciation of the effects attributable to sealing. If data were available on the levels of indoor air quality prior to sealing a better understanding could be developed. Without this information one can consider the data as a possible indication of potential levels in this type of house. Based upon the analysis it is possible to draw some inferences from the data.

One quarter of the formaldehyde results from similar houses could be expected to be above the action level of 50 ppb set for this study. To provide a better understanding of these apparently high results it is recommended that attempts be made to identify sources of formaldehyde in these houses. In addition, attempts should be made to reduce the levels.

One in six of the radon readings can be expected to be above the action level of 5 pCi/L. The high levels of radon detected in some houses should be further investigated and remedial work should be considered if the levels remain high.

Only two carbon monoxide levels were recorded above the 2.5 ppm action level. At the levels of carbon monoxide monitored in the various houses it is not anticipated that this compound will cause any problems. Detailed distribution analyses for carbon monoxide were not undertaken.

No data on the health effects of nitric oxide are available for levels as low as those recorded during this study. While approximately 7 percent of the measurements in similar houses can be anticipated to exceed the 0.5 ppm action level.

With respect to the nitrogen dioxide levels, the highest concentration measured in the houses could cause problems for sensitive individuals. Only one house in one hundred would be anticipated to have nitrogen dioxide levels above 0.15 ppm. The results show that homes with gas ranges are more susceptible to this condition.

The levels of carbon dioxide found in the study are not anticipated to cause any problems. High levels provide a good indication of the lack of ventilation in some areas of the houses. Fully 25 percent of all measurements could be above the action level, 600 ppm. It is suggested that the circulation pattern in homes be examined if high levels are recorded.

Relative humidity levels recorded during the study showed that most of the houses are in the commonly accepted range. In the houses where relative humidities were above the recommended maximum for the outdoor temperatures on the day of testing, the elevated humidities could lead to moisture problems. The highest moisture level recorded in any of the test homes was 67%. Such an excessive moisture content can lead to problems.

Air exchange rates measured using the SF_6 testing technique ranged from a low of 0.11 air changes per hour (ACH) to a high of 1.92 ACH. One value of 0.0 ACH was discounted due to measurement difficulties as was the positive slope for the changes in SF_6 levels in another house. Some differences in measured ACH values are present between the initial test and the second test in the houses. Generally no correlations was found between air change rates, infiltration rates calculated by the air sealing contractors, or indoor air quality results from this testing program.

Both oil and gas furnaces were checked for combustion characteristics. No substantial differences occur in carbon dioxide concentration in any of the furnaces regardless of the number of exhaust devices operating in the house. Sufficient scatter exists in the data to indicate that the exhaust gas carbon dioxide concentration is not strongly affected by the negative pressures inside the house. It should be noted that the negative pressures expressed in this report are purely those superimposed on the house by operating various exhaust devices. No consideration was given to the effects of wind or temperature gradients which influence infiltration rates. Such conditions may produce some substantial changes in carbon dioxide concentrations.

Stack draft measurements, in inches of water column, vary with changes in the number of exhaust devices in the house. Typically there is a marginal decrease in draft negative pressure as the number of operating exhaust devices increases. However, in one house, substantial variations were noted. Erratic behaviour occurred on the stack draft gauge

TABLE 1-1: DISTRIBUTION ANALYSIS OF CHEMICAL CONTAMINANTS

Chemical	Action Level	Median	Mean	90 Percentile	Percentage Greater than Action Level
Formaldehyde	50 ppb	35	41	70	25
Carbon Dioxide	600 ppm				
Bedroom		300	355	620	12
Main Floor		550	1700	3700	46
Basement		200	680	1500	21
Nitric Oxide	0.5 ppm				
Bedroom		4.4	26	65	13
Main Floor		4.8	19	40	8
Basement		3.9	5.1	10	1
Nitrogen Dioxide	0.15 ppm				
Bedroom		3.9	4.9	6.4	1
Main Floor		4.2	5.0	8.4	1
Basement		4.2	5.3	9.0	1
Radon	5 pCi/L	1.9	3.0	6.7	17

when the clothes dryer and all other exhaust devices were operating. The negative pressure induced by the dryer and the additional exhaust devices was sufficient to cause reverse flow in the fireplace chimney and the house filled with smoke. At no time did the furnace appear to operate improperly even under these extreme conditions.

1.4 Discussion

Several areas of the study require further comment. These are:

- o general approach,
- o radon measurements,
- o formaldehyde measurements,
- o nitrogen oxide levels, and
- o building ventilation.

While it is recognized that air sealing may add to problems with indoor air quality such issues must be dealt with on a case-by-case basis. For instance, an unsealed house with no exhaust fan and a gas stove has the potential for higher levels of contamination than an unsealed house with an electric range and plenty of exhaust fans. Clearly, there is a need for studies to document normal situations in houses that are unsealed and situations arising in houses after sealing. Only when one can compare, on a controlled basis, this type of data can one state the effect of air sealing. Given this limitation it is only possible to suggest areas that may require additional investigation on the basis of this study.

The radon measurements show three houses with radon levels above 5 pCi/L. The distribution of radon data is log normal and one function adequately describes the values in all houses. Two values appear to be on the high end of the 95% confidence limit and thus should be re-examined. Further analysis on radon levels revealed that there may be two general groups of houses existing in the Cambridge area with respect to their radon concentrations. Further work may define these apparent differences.

Any additional work on measuring radon levels in the various houses should involve repeating the track etch testing in a limited amount of homes. In addition, confirmation of the actual working levels in the houses with high readings should be conducted with real time instrumentation. If high levels are confirmed, additional testing for source

identification should be undertaken so that remedial measures can be selected to lower potential exposures to radon and its progeny.

Six houses had formaldehyde concentrations above the 0.5 ppm action level. In one case, new kitchen cabinets are suspected of being the major source of formaldehyde. In a second house, lack of ventilation, a gas range and smoking contribute to high levels. In these cases, and the other four houses, an increase in the ventilation rate through the use of exhaust fans should control most potential effects. Unfortunately, with formaldehyde's known role as an allergen, reducing levels may not decrease the noted response from sensitized individuals.

Only two houses recorded NO_2 levels above the 0.15 ppm action level. The presence of a gas range and poor ventilation in house 44 contributes to the higher levels of this pollutant. Ventilation rates should be increased in this house. In house 43 furnace operation should be checked to assess if poor operation is the major contributor to the recorded NO_2 levels.

In general, air sealing a house with an existing marginal air quality level could cause further deterioration of the indoor air quality. Further testing must be conducted to provide a conciusive means of defining the extent of the potential reduction in air quality. Caution should be exercised to ensure adequate ventilation exists to handle the gas generated by devices such as gas ranges. Moisture levels in houses should be examined before air sealing is undertaken. The owners should be instructed to watch for obvious signs of excessive moisture generation rates. Should these become apparent they should also have some information about lifestyle modifications to reduce the problem.

1.5 Conclusions

Air sealing will, no doubt, reduce energy consumption rates. It will also protect the structural members of the house. It could, however, also affect indoor air quality. The extent of the effect and the limit of allowable levels of indoor air quality are yet to be determined. Until such time as both data for acceptable indoor air quality levels for houses and a method for determining potential levels after air sealing is developed it would be wise to:

- establish an arbitrary tightness limit to minimize the potential for overtightening a home,
- limit air sealing to homes without major sources of contaminants or excessive moisture, (i.e., do not seal homes with gas ranges unless they are equipped with exhaust hoods),
- make sure the homeowner understands the limitation of the process and will modify his lifestyle to reduce air contaminants and moisture levels in the house.

2.0 INTRODUCTION

Some activities inside houses have the potential to produce air contaminants. Typical activities that create the contaminants include:

- o smoking;
- o cooking;
- o heating (including fireplaces and water heaters); and
- o cleaning (including use of solvents, air purifiers, and fabric softeners for clothes, and water vapour from baths and showers).

Even the introduction of new materials can produce increased levels of air contamination. Common air pollutants include:

- o carbon monoxide and carbon dioxide;
- o oxides of nitrogen (both nitric oxide (NO) and nitrogen dioxide (NO_2));
- o radon and its daughter products; and,
- o formaldehyde.

While not truly a pollutant, water vapour can have detrimental effects on structures and finishes; as such it must also be considered. In addition increased levels of humidity in homes have been observed to increase the occurrence of house dust mites (Korsgaard, 1979) and promote the growth of fungi (Pers. Comm. G. White).

While these contaminants result from activities inside the house they also exist outside. Some studies have shown that the ratio of indoor to outdoor air contaminant levels is usually a function of the operations in the house, (Yocom, 1982). For instance carbon dioxide (CO_2) is higher in houses with unvented combustion activities such as kerosene heaters and gas stoves. With these appliances, oxides of nitrogen (NO_x) and carbon monoxide (CO) are twice outdoor levels, without them the indoor levels are typically half outdoor levels. Radon, a product of the decay of Radium is present in trace quantities in most soil. It can seep into basements and will accumulate there. Radon can also result from emissions from building materials and water introduced to the house (Bruno, 1983). Formaldehyde is present in many items generally found in the home. The rate at which it enters the atmosphere is a function of temperature, humidity and concentration.

All these pollutants would continue to accumulate in the house if it was not ventilated. Normal ventilation due to the exhausting of:

- o combustion products from furnaces and fireplaces, and
- o moisture and odours from kitchens and bathrooms,

creates a negative pressure in the house which promotes the infiltration of fresh air. If the house is sealed, and particularily if it is "super-sealed" in an effort to reduce energy consumption, this negative pressure may not induce as much infiltration. In fact it is possible to have a house so well sealed that reverse flow may occur in chimneys and fireplace flues when other exhaust sources are operated. This can produce dangerous levels of air contamination in the house.

The first indicators of ineffective ventilation in a house are the presence of excessive condensation on cold surfaces and the build-up of odours. These indicators have been noticed in some of the homes retrofitted during a Ontario Ministry of Municipal Affairs and Housing (MMAH) sponsored Weatherize project. Due to these observations air quality testing was undertaken to quickly ascertain if any other problems existed with indoor air quality (IAQ) in these homes.

The Ministry of Municipal Affairs and Housing contracted IEC Beak Consultants Ltd., with funds provided by the Ministry of Energy under the Housing Energy Management Program (H.E.M.P.), to screen indoor air quality (IAQ) in twenty of the demonstration homes. These homes were all located in Cambridge, Ontario. Work was conducted during late March and April 1983.

The following report presents the results of the testing program. Additional tests, not originally included in the Scope of Work, but also addressing IAQ issues in energy efficient houses, are discussed in two other reports.

- o A Special Study of Indoor Air Quality in an Energy Efficient House - Howland House;
- o A Special Study of Polyurethane Foam Off-Gassing in Houses.

3.0 TECHNICAL APPROACH

3.1 Rationale

As noted in the introduction, numerous sources of airborne contaminants exist in any house. The development of any approach to evaluating the levels of these materials in the house must recognize the inter-relationships that exist between:

- o ventilation rates,
- o sources,
- o occupancy patterns, and
- o lifestyle of the occupants,

in the house. While these relationships can be complicated any study must recognize that they exist and attempt to collect data on all the different issues. Such an approach was used for this screening study and while all the cause-effect relationships may not be completely defined the project does identify areas for future review.

To accomplish the collection of the relevant data, a four step approach was utilized. Sources and occupancy patterns were identified through inspection and the use of a questionnaire; ventilation rates were established by tracer gas tests; indoor air quality (IAQ) levels were ascertained through short and long term sampling; and, potential relationships between the sources and IAQ were further examined with combustion tests. Details of the various study phases are outlined in this section of the report.

3.2 Homeowner Questionnaire

Different lifestyles and occupancy patterns can produce variations in indoor air quality. Some standard data on these factors were obtained for each house.

A questionnaire cannot cover all the activities or situations which affect the indoor air quality, however, a standard set of data gathered for each house was considered necessary to assist in interpreting IAQ results. These data were supplemented with personal observations in each residence.

In an effort to maintain a high level of response and a uniform interpretation of the questions, all of the questionnaires were completed by a single field technician (with the assistance of the homeowner). The standard set of data generated for each house was classified into the following eight sections:

- o dwelling description;
- o occupant information;
- o heating;
- o humidity/ventilation;
- o water usage;
- o cooking;
- o assessment of home comfort levels; and
- o indication of problems.

The questionnaire is appended (Appendix 1), and the questionnaire results are summarized in Chapter 4.0. A brief description of the types of questions in each of the eight sections follows.

3.2.1 Dwelling Description

The objectives of this section were: (1) to document the degree of weatherizing; (2) to provide a physical profile of the residence; (3) to evaluate the physical condition of the residence; and (4) to record differences between the residents' activities which could alter indoor air quality. The approach to these objectives was to record data under the following ten sections.

- o The present insulation (the type of insulation, its location and thicknesses)
- o Recent energy retrofit activities (the dates and nature of any recent activity which affected the air infiltration rate i.e., addition of storm doors or caulking)
- o Doors (particular emphasis was placed on the number and type of door and weatherstripping, i.e., one wood clad sliding glass door)
- o Type of dwelling (the type of house, i.e., single, duplex, as well as floor plan sketch provided a physical profile)
- o Basement (description and comments included physical conditions such as water stains, cracks, holes, etc.)

- o Dwelling internal analysis (general comments on the type and condition of walls, windows, ceiling and attic)
- o Dwelling exterior analysis (general comments on the type and condition of the roof, chimney, soffit, siding, paint and foundations)
- o Garage (the size and proximity to the house and the presence of interior access to the house. This latter situation may alter the indoor air quality not only by vehicular emissions but also by the storage of solvents, pesticides and garbage in the garage.)
- o Fireplaces (the presence of and the type of fireplace i.e., Franklin, built-in. The presence of and use of fireplaces can produce significant air quality differences between homes).
- o Miscellaneous (this category provided information about such areas as indoor plants - photosynthesis involves CO_2 to O_2 conversion, drapes - heat loss/heat gain due to material, aquariums - aerators and large open water surfaces contribute to the humidity, and air purifiers - where and why are they present).

3.2.2 Occupant Information

The purpose of this section was to assist in developing an understanding of the lifestyle of the residents as related to IAQ issues. The number of occupants, their ages, the number at home during the day and the number of smokers was deemed sufficient information for assessing indoor air quality stresses. Clearly this is not a sociology study, however, a retired older couple may have significantly different indoor air quality in their home than would a family with three young children and a dog. This data is important to the proper analysis of data trends.

3.2.3 Heating Equipment

Information collected on the house heating system was limited to the type of equipment and the normal thermostat settings in the house. The type of heating fuel (i.e., oil, gas, electric, coal, other) was recorded as a percentage of the total. Thus the occasional use of a fireplace for aesthetic purpose was separated from the use of a fireplace as a heating unit. The 'normal' thermostat setting for day and night were recorded as well as a subjective question on the frequency of setting the thermostat down at night. As the study was conducted during the winter, no emphasis was placed on air conditioning.

3.2.4 Humidity and Ventilation

The humidity questions were specific to homes with humidity control either in the form of a portable console type humidifier or a built-in furnace unit. The ventilation questions dealt with the use of dryer exhausts or other exhaust fans and the setting of the fireplace damper. A subjective question was asked on the degree of difficulty experienced in starting a fire in the fireplace and how well the fireplace operated. Poor operation produces excess smoke input into the house during fireplace start-up thereby causing increased levels of indoor air contaminants, and indicating that insufficient make-up air may limit the proper operation of other devices.

3.2.5 Water Usage

Water usage in the house has the potential to affect the relative humidity, and as a consequence, the heat capacity of the air. This can lead to modifications of the comfort setting in the home. Furthermore, water use for cooking, washing or bathing has the potential to release the radon gas that may be present in it thereby increasing indoor radon concentrations.

The use of perfumes, softeners and detergents can contribute to organic air contaminant loads in the house. Lifestyle questions pertaining to monthly water consumption, and the use of dishwashers, laundry devices and cleaners were recorded to document any special cases which may occur.

3.2.6 Cooking

Data collected on cooking was limited to the type of range (gas, electric, other) and a profile of cooking techniques (frying, broiling, baking, etc.) ranked by frequency. The organic loading to atmosphere from frying is potentially larger than other methods. In addition, gas ranges has long been recognized as a major source to the deterioration of indoor air quality.

3.2.7 Home Comfort Levels

The assessment of home comfort levels by the resident dealt with humidity, temperature

(air and floor) odours and drafts. This data provides two important responses: how major a problem the homeowner perceives and where these problems occur. This response can be used to assess infiltration problems and also provide indications of poor circulation in the home. Poor circulation can give rise to localized elevated levels of indoor air contaminants.

3.2.8 Indication of Problems

To aid in the identification of potential structural problems in the house due to energy sealing a checklist was developed. Issues such as water marks or stains, rot, mould, moisture in insulation, and cracking and peeling of paint were keyed for examination of the attic, ceiling, walls, windows and basement.

3.2.9 Questionnaire Application

Some additional questions were developed to standardize this study with other Ministry sponsored projects. Responses judged not to affect indoor air quality were not tabulated for this report. Furthermore areas showing no significant differences were not tabulated. Results are summarized in Chapter 4.

3.3 Measurement of Indoor Air Quality and Other Parameters

The measurements of airborne contaminant levels can be conducted in a number of ways depending upon:

- o the pollutant;
- o the concentration of the pollutants;
- o the source of the pollutants;
- o the receptor of the pollutants; and
- o the ultimate goal of the measurement of levels.

Traditionally airborne contaminants are released from sources, usually stacks of combustion or process ventilation systems or from automobiles, etc., and they disperse in the atmosphere. Scientists require source emission measurements to aid in modifying processes either to improve performance and efficiency or to predict the effect that the emissions will have on the environment. Industrial hygiene experts measure air

contaminant levels inside industrial facilities to assess the exposure of worker to potentially toxic materials. Ambient air quality levels are measured by scientists to monitor the level of criteria pollutants in the atmosphere. Since ambient levels are the result of the release and dispersion of all emissions to the atmosphere, outdoor levels are traditionally much lower than either stack or industrial levels. Measurement of ambient levels is more difficult and requires highly sophisticated equipment. Simplified methods can be used to achieve the measurement objectives of this study to sample IAQ levels, but are limited in their ability to provide the data required for cause effect analysis.

When trying to establish many of the relationships between use and indoor air quality the ideal situation would be to collect continuous instantaneous readings of contaminant levels in the house and match them to occupant activities. Obviously, for a sampling study, this is not practical due to time and cost limitations. Similarly, given the broad range of organic compounds that may be present in indoor air, it is impractical to consider extensive studies of organic contaminants. Thus this study was confined to utilizing established simplified methods for measuring common contaminants in the air.

The contaminants chosen for this study were:

- o carbon monoxide (CO);
- o carbon dioxide (CO_2);
- o nitric oxide (NO);
- o nitrogen dioxide (NO_2);
- o radon (including decay products); and
- o formaldehyde.

The indoor comfort conditions,

- o temperature, and,
- o relative humdity,

were measured along with outdoor conditions such as:

- o temperature;
- o relative humidity;

- o wind speed;
- o wind direction; and,
- o barometric pressure.

Details of the methods utilized and their limitations are provided in this section.

3.3.1 Measurement of Carbon Monoxide and Carbon Dioxide

Principal

The measurement of carbon monoxide (CO) and carbon dioxide (CO_2) were conducted with long term Draeger tubes. A known volume of air at a standard flow rate is drawn through a glass tube containing a solid adsorbent. A reagent within the tube reacts with the given contaminant to produce a colour change. The length of colour change is proportional to the quantity of the contaminant in the air being tested. The tubes used for this study were designated as carbon monoxide - 10/a-L and carbon dioxide - 1000/a-L.

In the case of carbon monoxide (CO) the indication is based on a colour reaction with iodine pentoxide, selenium dioxide and fuming sulphuric acid. The colour change in the carbon dioxide tube (CO_2) occurs when the CO_2 reacts with an alkali and the indicator measures the depletion of the alkali.

Sample Collection and Analytical Methods

Both tests were conducted at a flow rate of 20 cc/min for two hours. Separate pumps were utilized for each CO and CO_2 measurement. The pump was an Accuhaler Model 308 equipped with an orifice which limited the flow to the required rate. The flow rate of the pumps was routinely checked using the Accuhaler Calibration kit. The length of stain on the tubes was then read to provide the total microliters of contaminant collected. This value is divided by the total sample volume in litres, to provide a concentration in parts per million (ppm). Since the tubes were calibrated for air at 20°C and 1013 mbar atmospheric pressure, the sample volume is corrected to standard temperature and pressure (STP).

Range of Measurement

The calibrated ranges over which the tubes operate are 10 to 100 microliters of CO and 1000 to 6000 microlitres of CO_2 (Draeger, 1a,1b). Results from sampling were interpolated to one half of the low end range of the tubes. At the flow rates used, barring correction for temperature and pressure, this corresponds to CO - 2-20 ppm and CO_2 - 200 -2500 ppm for a two hour sample. On occasion it was noted that the colour change occurred very rapidly. Under these circumstances the pump was shut off early thereby raising the effective upper level of detection. With a minimum of 1 litre sample size the upper level of CO_2 detection is 6000 ppm.

The federal government desirable ambient (outdoor) air quality objective for CO is 0-17 ppm (0-15 mg/m^3) for one hour average concentrations and 0-7 ppm (0-6 mg/m^3) for eight hours. The minimum detection limit for CO thus lies below any criteria available.

The lower limit of detection for CO_2 is below the normal concentrations of this substance in the atmosphere (300-400 ppm). The Ontario Ministry of Labour caution that eight hour exposures to levels in excess of 600 ppm can lead to headaches and other physical ailments. Furthermore they suggest that 800 ppm levels require remedial measures consideration (Pelmear, 1983). As noted above, the tube is satisfactory for measuring levels well below the effect levels.

Interferences

Interferences in the measurement of the gases were also considered. The carbon monoxide tube will respond to levels of certain organics. For instance 100 ppm of acetylene will produce a 30 ppm response, 100 ppm of benzene would produce 10 ppm readings. The carbon dioxide tube is not sensitive to 500 ppm of H_2S, HCl, SO_2 or NO_2 or 100 ppm of NH_3.

Both tubes were satisfactory for use in the indoor environment temperature range. The CO tube must be used above 5^oC, the CO_2 tube above 0^oC. Outdoor measurements at 15 locations may therefore not be entirely satisfactory due to temperature limitation. The upper humidity level for operation is limited to 15 mg H_2O per litre of air for CO_2 and 30 mg H_2O per litre of air for CO. Calculated ranges for the test conditions are in the

range of 6-9 mg H_2O per litre. Incidental errors in measurements with these tubes are not listed by the manufacturer.

3.3.2 Measurement of Nitric Oxide and Nitrogen Dioxide

Principle

The nitric oxide (NO) and nitrogen dioxide (NO_2) sampling employed three section sorbent tubes. The principle is to draw air at a specific rate through the tubes whereupon NO_2 is adsorbed in the first section, NO is converted to NO_2 by an oxidizer in the second section and the NO_2 is adsorbed in the third section. The first and third sections, containing molecular sieve impregnated with triethanolamine (TEA), are desorbed in water. The nitrite in solution is determined spectrophotometrically using Griess-Saltzman Reaction. The nitrite found in the first section is reported as NO_2 and the nitrite in the third section is reported as NO. The method is a variation of both the NIOSH (1977) manual method (P & CAM 231) and the APHA method P & CAM 210 (Katz, 1977). The modification involves the use of the tandem sections of TEA coated sorbent and the oxidizer.

Sample Collection and Analytical Methods

Standard tubes were purchased from SKC, Inc., in Pennsylvania, (Catalogue No. 226-40). They were utilized with a DuPont PM4000 personnel monitoring pump calibrated at 100 cc/min. and run for four hours. The pumps were routinely checked using a Kurz mass flow meter. The tubes were then sealed and returned to the laboratory for analysis.

In the laboratory the tubes were emptied, taking care to separate the first section of TEA coated sorbent into one labelled container and the 2nd into a 2nd container. Twenty-five millilitres of the desorbing solution, (15 g of TEA, 500 ml of distilled water, and 0.5 ml of n-butanol diluted to 1 litre) are added to each container. The containers are shaken and 10 ml of the resulting solution are transferred to another container. The colour is developed after the addition of 1 ml of 0.02% hydrogen peroxide solution, 10 ml of sulfanilanide solution and 1.4 ml of NEDA solution. The resulting colour is read on the spectrophotometer at 540 nm with a blank reference cell.

The concentration of NO_2 in ppm is calculated as follows:

$$p = \frac{\text{ug } NO_2 \times 0.532}{\text{volume sampled @ STP}}$$

where p = concentration in ppm

$ugNO_2$ = calculate quantity collected by conversion of absorbance units to ug per 25 mL using standardization curve

volume = flow rate (l/min) x time (min.) (with flow rate corrected to 25°C and 101.2 kPa)

and 0.532 is the conversion factor NO_2 to ul NO_2 at 25°C and 101.2 kPa.

Range and Accuracy

The P & CAM 210 method states that the range of the method is 0.01 - 10 ppm of NO_2 in a 72-96 litre sample. The range has been validated for 0.005 ppm to 0.5 ppm but not for 0.5-3.1 ppm concentrations of NO_2. The sensitivity of the method is noted to be dependant on that of the Griess-Saltzman reagent and the accuracy of reading absorbance units on the spectrophotometer. The absorption efficiency is stated as 95% up to 0.5 ppm concentrations.

The modification employed in this study should be suitable for NO sampling since P & CAM 231 states that the oxidizer should be good for up to 50 ppm of NO oxidation. The expected range of NO (as NO_2) lies in the range of the method P & CAM 210.

Interferences

Limited data on interferences with the method are reported. Organic nitrites and peroxyacetyl nitrate (PAN) compounds can interfere positively but such interference is not quantified. SO_2 at 0.13 ppm, ozone up to 0.5 ppm and NO at 0.6 ppm do not produce interferences.

Two cautions must be included under interferences. P & CAM 231 notes that the

presence of moisture in the tube can severely reduce the breakthrough volume of the tube. This implies that determination may not be accurate since some NO_2 may not be scrubbed out of the air if moisture builds up in the tubes. Secondly, P & CAM 210 uses a longer tube of smaller ID than that used for this study. This may influence the adsorption rate as channelling can occur more readily in larger tubes.

3.3.3 Measurement of Radon

Principle and Method

The radon sampling employed Track Etch, Type F, radon dosimeters manufactured by Terradex Corp. Walnut Grove, California. These dosimeters are based on the principle that alpha particles, bombarding the alpha sensitive plastic detector, leave radiation damage tracks. The tracks are subsequently revealed by caustic etching and counting under a 500x microscope. The number of tracks counted per unit area is proportional to the average exposure rate (pCi/l) and the exposure time (Alter, 1981). The Type F dosimeter is specific for radon gas only. It is equipped with a filter to eliminate dust and airborne daughter products from the inside of the sampler. The track etch chip is fastened to the bottom of a plastic cup and the filter is placed over the mouth of the cup.

Sampling was performed in the basement of each of the homes. This involved exposing a plastic cup containing the detector at floor level for a period of 20-44 days. An inconspicuous location was chosen for the plastic cup. The cups were then carefully sealed and sent to Terradex Corporation for analysis. Outdoor samples were collected at the same time as indoor samples at ten representative locations.

Calibration and Sensitivity

Calibration of the devices is undertaken, by the manufacturer, in an exposure chamber with a known radon source and a well characterized knowledge of particle size and daughter product equilibrium. Continuous monitoring for radon is conducted at the same time as the dosimeters are exposed. Calibration factors are devised dividing the track density by the radon exposure (Alter, 1981).

Sensitivity of the method is a function of the area counted under the microscope. With a count area of 17.25 mm^2 (300 fields) the sensitivity is sufficient to measure average ambient outdoor radon at 0.2 pCi/l for exposure times of 1-2 months. This is adequate for a variety of outdoor and indoor measurements.

3.3.4 Measurement of Formaldehyde

Principle

The formaldehyde sampling employed AQR Passive Dosimeters manufactured by Air Quality Research Inc. International. These dosimeters work on the principle of diffusion and absorption of formaldehyde onto a filter treated with sodium bisulphite. The room air and formaldehyde diffuse into a glass vial which has the bisulphite coated filter at the closed end.

The diffusion of the formaldehyde is accomplished through the open end of the vial. The rate at which the diffusion takes place is governed by classical diffusion laws, (Fowler, 1982). The diffusion transport rate is integrated over the length of the tube to provide an expression for the sampling rate. For the AQR devices the sampling rate is 4.1 cc/min.

Sampling and Analytical Method

An average of two dosimeters were placed in each home with an additional dosimeter placed outside. In some cases three were placed inside, two of these side-by-side as a quality control check. Sites were open and unobstructed to allow free flow of air. The dosimeters were at least one foot away from any large flat wall, and were not placed in a closed corner of any kind. They were also placed two metres off the floor. Known sources of formaldehyde , e.g., combustion appliances, particle board, etc., were taken into consideration so that dosimeters were not placed within two feet of these sources. The dosimeters were left for six to thirteen days. They were then capped and returned to the laboratory for analysis.

Dosimeters were analysed using the chromotropic acid method (BAS-NRC Method Two). Briefly, each AQR filter was desorbed with deionized distilled water. A colour was

developed using 5% chromotropic acid salt solution and sulphuric acid. After complete colour development the absorbances were read at 580 nm wavelength on a 10 mm path length flow cell equipped spectrophotometer. These absorbances were compared to a standard curve of known concentrations. The calculations were as follows:

$$\text{Working slope} = \frac{\text{A.U.}}{\text{mL}} \times \frac{\text{ml}}{\text{ug}} \times 2.00\ \text{mL}$$

where $\frac{\text{A.U.}}{\text{mL}}$ is the actual slope of the data, and

ml/mg is the concentration of standard HCHO solution (about 10)

$$\text{Total ug} = \frac{\text{Sample Absorbance-Blank Absorbance}}{\text{Working Slope}} \times 4$$

$$\text{Total ppm-hr} = \frac{\text{Total ug}}{0.303}$$

$$\text{TWA ppm} = \frac{\text{Total ppm-hr}}{\text{Exposure time in hours}}$$

Range and Sensitivity

The lower end of the range of the samplers is dictated by the blank variability. This typically runs from 4 - 20 ppb. The upper end of the range is proportional to exposure time, but the total capacity of the dosimeter can confidently be stated to be about 50 ppm hours. They can, however, be pushed to higher levels depending on humidity and other issues that influence the recovery efficiency.

Studies of precision and accuracy show wide variability depending upon exposure. Well placed units have however been shown to be within 5% on precision and accuracy (IEC BEAK, 1983).

Interferences

Interferences with the operation of the units are produced by poor placement of the dosimeters which influences the diffusion rate. Such changes in the sampling rate are not readily documented nor can they be compensated for in calculations. Placement is thus critical.

No definite chemical values are currently available for sampling induced interferences, however, studies have shown extremely high levels in laundry areas. This may be due to formaldehyde in detergents and fabric softeners or to other chemicals. These problems are usually overcome by siting the samplers in areas where detergents are known not to be used. Other aldehydes are also known to respond positively during analysis.

Recovery problems have been noted due to the presence of oxidizing compounds and high humidity, however, no definite documentation is yet available.

3.3.5 Measurement of Climate and Meteorological Parameters

For each of the sampling days the Breslau Weather Station was consulted for barometric pressure, wind speed, and direction. Both wet bulb and dry bulb temperatures were taken with a psychrometer at each of the homes. The wet bulb thermometer was not accurate below $0^{\circ}C$ and Breslau data for temperature and relative humidity were obtained for these cases. Using both the wet and dry bulb temperatures, the relative humidity could be calculated.

Barometric pressure variations along with temperatures are required when utilizing pumps to sample air. Volumetric changes occur with these systems and the volumes must be corrected to Standard Temperature and Pressure (S.T.P.). Wind speed and direction are important for interpreting data, as these factors can affect house infiltration rates.

Temperatures and relative humidity data was also gathered from inside the house at each sampling location.

3.3.6 Measurement of Air Exchange Rates

Principle

Sulfur hexaflouride (SF_6) was used as a tracer gas for determining the air exchange rate for each of the homes. This method is outlined in ASTM Standard E741 and was modified by NRC (1982). A measured amount of SF_6 gas is injected into the return air duct of a furnace ahead of the fan and withdrawing a number of samples after specific elapsed times. In the case of electrically heated homes with no furnace tracer gas was injected into the living room air and sampled at the same point after suitable elapsed time intervals. The level of SF_6 in subsequent samples can be utilized to calculate the concentration decay rate and thus infiltration rates.

Sampling and Analytical Method

A small hole was drilled into the return air duct to accommodate a syringe. With the furnace fan operating, 20 ml of SF_6 gas was injected. Following injection time lapse samples were taken at 30 min., 40 min. and 60 min.

A second set of SF_6 tests were done for the nine of the twenty homes chosen for combustion tests. Similar conditions prevailed during this testing and the technique was modified to provide more accurate results. In these cases 50 ml of SF_6 gas was injected and five samples were taken at elapsed times of 15, 30, 60, 90 and 120 min.

A fresh 30 ml syringe was used to obtain each sample. The needle was inserted into the return air duct and the syringe was flushed by drawing the plunger from 0-30 ml and then pushing the plunger back to zero. To be most effective the plunger was always moved slowly. The gas sample was collected by slowly pulling the plunger of the syringe to the 30 ml mark. The plunger was then pushed back to the 25 ml mark.

The needle of the syringe was then inserted into the septum of a 10 ml Becton-Dickenson Vacutainer (no additive). The plunger was drawn by the vacuum to about 17 ml mark (failure to do this indicated a faulty Vacutainer). After the plunger stopped it was slowly pushed to the 2 ml mark and held there for approximately 15 seconds. The needle was then removed from the septum. With this procedure the gas sample in the Vacutainer

was under pressure (about one atmosphere above ambient). The sample was analysed using a gas chromatograph containing a 13x Molecular sieve column and an electron capture detector. Qualitative standards were analysed to ensure that the chromatogram represented SF_6 concentrations. All injections utilized a gas tight syringe. Once all samples had been injected, the peak heights were used to quantify SF_6 concentrations.

The time and SF_6 concentrations (represented by peak height) were fitted to a regression line to ascertain decay rates. Infiltration rates were then calculated using the following equation

$$I = (\ln(C_i/C_o))/(t_i-t_o)$$

where I = infiltration rate, air changes per unit time
C_i = concentration at time, t_i
C_o = concentration at time, t_o

Sensitivity and Range

Given the ability of the gas chromatograph (GC) to accurately identify SF_6 in samples, (a distinct peak occurs with no other noted interferences), the range and sensitivity of the method is a function of:

- the time between samples,
- the SF_6 concentration, and
- the sample size injected into the GC.

No specific tests were run to quantitate SF_6 concentrations for this study. Rather peak heights were used as a proportional indication of concentration. Sivertsen (1983) reports that GC analysis techniques are capable of 2×10^{-12} parts SF_6/part of air lower detection limits. Furthermore, he states that the useful analytical range is 2 to 10^6 ppt (2×10^{-12} - 10^{-6} parts SF_6/part air). This extreme sensitivity is very useful because it limits the amount of SF_6 injected. With background levels of 0.4 ppt interference of readings is also not a consideration (Sivertsen 1983).

On the basis of the foregoing, there appears to be little problem with measuring SF_6 concentations. The precision of the method is currently unknown. ASTM E741 states that the uncertainty of the method is about 10%.

Interferences

The tracer gas, SF_6, is relatively unreactive. The gas does not occur naturally and thus internal sources in houses will not exist. No spurious influences can effect sampled levels due to the specific nature of the analytical technique.

It was noted by NRC (1982) that samples can be stored for up to 21 days without significant changes, also that there are no significant differences in concentration when exposed to extreme temperatures (-10°C to 36°C).

The specific nature of the analytical technique allowed analysis to be uninfluenced by other materials present in the air.

ASTM E741 notes that infiltration rates are a strong function of wind speed, direction and temperature differences. These factors must be considered when looking at any results.

3.3.7 Measurement of Combustion Products

Principle

Combustion products testing was undertaken on a limited number of houses. CO_2 levels in furnace exhausts were measured using a Fyrite CO_2 analyser. The analyser employs a volumetric analysis involving chemical absorption of CO_2 gas by potassium hydroxide. The sample is drawn into the Fyrite by an aspirator bulb and any CO_2 is absorbed by the potassium hydroxide. The level of the potassium hydroxide will increase in proportion to the percent CO_2 in the sample, and this increase can be read off the scale on the side of the instrument as a percentage of CO_2.

Method of Sampling

Samples were taken at the end of the combustion chamber (or chambers in multi chamber gas furnaces) and midway along the exhaust duct (after the dilution air inlet). When samples could not be obtained directly inside or at the end of the combustion chamber, readings were taken in the duct before the dilution air inlet. Replicate samples were taken to confirm the first result.

Range and Interferences

The Fyrite measures CO_2 in a range of 0-20% (Bacharach, 1980). It can be operated at temperatures from -34°C to 66°C and hot gases can be injected into the unit. The limit of measurement is the interpretation of the scale on the instrument.

Acid gases such as SO_2, H_2S and liquid hydrogen cyanide, etc., produce a 1:1 interference with the measurement. These are not present in large quantities in residential furnaces and thus do not pose a problem.

Draft Measurements

A Bacharach draft gauge was utilized to measure the stack draft after the draft hood in all chimneys. This instrument reads the negative pressure in the stack in inches of water column.

Gas fired appliances, furnaces and water heaters particularly, are recognized to have a more sensitive relationship between the burner, draft hood and stack than oil furnaces. Atmospheric gas burners do not have the mechanical ventilation ability of oil burners and therefore temporary difficulties may be experienced during start-up if the house is under severe negative pressure.

3.4 Selection of Test Houses

3.4.1 General Survey

The Ministry of Municipal Affairs and Housing specified that all twenty homes in Cambridge would be subjected to general monitoring. Cambridge is composed of the three former towns of Galt, Hespeler and Preston. Study homes were located in each community. A list of homes are appended in Appendix 1. The homes will be referred to only by number (31-50) throughout this report.

Homes 31, 33, 36, 39, 41, 42, 43, 46, 47, 48 and 49 are in Galt.

Homes 32, 34, 35, 40 and 45 are located in Hespeler.

Homes 37, 38, 44 and 50 are in Preston.

3.4.2 Combustion Testing

Combustion testing was undertaken after the results of the general survey in all the homes were available. The purpose of combustion testing was to identify conditions that may induce a reverse draft in the stack. As this situation is a function of:

- o the house size (chimney height),
- o the volume of the house,
- o the infiltration rate, and,
- o the installed exhaust capacity,

these issues were used to develop a selection criteria.

The initial survey defined the size and type of structure for each house. The study also determined the number and capacity of installed exhaust fans, the presence or absence of a fireplace, the type of water heating system (oil, gas or electric), the type of clothes dryer (gas or electric) and if a fresh air source was available in the home heating system. An initial measurement of infiltration rates using the SF_6 tracer gas method provided a scale for assessing the suitability of houses for testing.

Five of the 20 houses were electrically heated and thus immediately eliminated (33,37,38,41,46). Of the remaining 15 only 6 houses have fireplaces (31, 34, 35, 40, 47, 48). A combination of the factors outlined above were used to select from the 15 houses, the nine homes for combustion testing.

Low infiltration rates formed the initial selection criteria. In order of infiltration rate the six lowest houses were 50, 44, 49, 47, 31 and 35. Their infiltration rates ranged from 0.0 to 0.38 air changes per hour (ACH). The next three houses in order of measured infiltration rate (36, 43 and 45) were eliminated on the basis of limited installed exhaust capacity. House 32 (0.60 ACH) had noticeable moisture problems. As this raised some concern about the accuracy of the measured infiltration rate the house was added to the test list.

The last two houses selected were, house 48 at 0.72 ACH and house 42 at 1.62 ACH. House 48 has a fireplace. House 42 has a high installed exhuast capacity (2 fans, a dryer and a gas water heater). House 42 also had the second highest infiltration rate and it was deemed prudent to check a high infiltration house as well as low ones for comparison purposes.

3.5 Selection of Test Locations

Generally an area on each floor of the house was selected for testing (basement, main and second floors). Formaldehyde was usually measured in the living room, and a bedroom. Within the limitations of the sample methods outlined earlier, it was considered appropriate to sample only in areas of the house not containing known sources of potential formaldehyde interferences therefore, laundry rooms and kitchens were avoided. The testing for CO, CO_2, NO and NO_2 was carried out in a variety of rooms on the main floor. Kitchens were tested in homes with gas ranges otherwise locations were picked at the discretion of the technician. Radon samples were taken in the basement of each house as basements tend to have higher levels (Fleischer et al, 1982).

Outside measurements for all materials were generally on the upwind side of the house to sample air coming toward the house.

4.0 RESULTS OF MEASUREMENT STUDIES

4.1 Introduction

A number of different criteria are commonly used to ascertain the suitability of indoor air quality levels and the effects that these levels might have upon people. Primary among any criteria used for judging levels are standards, be they set for the outside ambient environment, indoor working exposures, or other purposes. As of 1984 residential Indoor Air Quality standards do not exist. Currently a Federal Provincial Working Group is studying this subject. The existing standards for ambient (outdoor) air quality and workplace exposure do, however, allow us to assess the measured levels with respect to criteria based on known toxicity and/or other effects on humans. Comparing values measured in a particular study with results from other studies can also prove valuable. A third method of reviewing the results is to compare the levels indoors to those levels found in the outdoor environment. This indoor/outdoor ratio technique is one that has generally been used in recent time to provide a indication of the significance of indoor air quality levels (Yocom, 1982), however, it is dependent on the location of the homes, i.e., downtown measurements may be quite different from suburban ones thereby masking the indoor source effects.

In addition to comparing current data with that generated in other studies, useful data can also be obtained by looking at variations within a particular household. For instance, ineffective circulation of air in houses may create localized "hot spots", where the pollutant concentration is higher than normally expected or desirable, or conversely areas of very low contamination. The dilution effect is important for many sources. Comparison of the measured levels in different areas of a house to the various types of sources located in these areas may provide a clue as to the appropriate remedial measures necessary to improve indoor air quality.

The development of measures to improve the indoor air quality is, of course, the ultimate goal of undertaking any screening program to determine indoor air quality levels. Such development must take into consideration all the factors outlined above. In this chapter of the report, we address the subjects and compare the standards, indoor/outdoor ratios, and other guidelines with the values measured in the Cambridge homes. Remedial measures for the various homes, are provided where they are considered appropriate.

4.2 Standards and Reported Levels

A detailed discussion of standards and levels is presented in Appendix 2. Some of the issues addressed in that appendix are summarized in this section.

Ambient air quality standards (AAQS) are defined for numerous substances. In addition, industrial hygiene levels are also defined for many contaminants. The various standards that are applicable for the substances measured in the Cambridge homes include:

- the Canadian Ambient Air Quality Objectives as set by the federal government and regulated by the various provinces (EPS, 1976),
- the United States National Primary and Secondary Ambient Air Quality Standards (40 CFR Part 50),
- the Workplace Threshold Limit Values published by American Conference of Governmental Industrial Hygienists (ACGIH, 1983),
- the Standards for Ventilation Required for Minimum Acceptable Indoor Air Quality published by American Society of Heating Refrigerating and Air Conditioning Engineers (ASHRAE, 1981),
- the Canadian Standards for Formaldehyde in UFFI homes (UFFI/ICC Criteria), and,
- Criteria for radon (AECB, 1977).

A summary of the most pertinent standards is provided in Table 4.1. The table presents the maximum acceptable levels for Canadian objectives although a more stringent "desirable" category is also contained in the legislation. Discussions on standards for each of the pollutants is presented in Appendix 2.

Appendix 2 also reviews the range of airborne concentrations for both indoor and outdoor air pollutants as reported in the literature. Much of this material relies upon the work of Small (1983) and other recent publications. The range of reported values are summarized in Table 4.1 as are the reported average values.

In some cases, indoor air quality standards have been based on outdoor measurements (ASHRAE, 1981). At best, monitoring outdoor air quality provides an indication of localized ambient air quality and is not applicable to the wide ranges of residences in

TABLE 4.1:

STANDARDS, REPORTED DATA, AND
SELECTION OF INDOOR AIR QUALITY CRITERIA

Contaminant	Outdoor Standards		Reported Outdoor Levels			Indoor Standards		Reported Indoor Level		I/O Ratio	Selected Action Level (ppm)
	Time Span	Level (ppm)	Time Span	Range (ppm)	Average (ppm)	Time Span	Level (ppm)	Range (ppm)	Maximum (ppm)		
Carbon Monoxide (CO)	Canada (Maximum acceptable)		Annual	0.8 - 3.2	1.7	ACGIH					
	-8 hour	10				-8 hour	50 ppm	0.5-5	100	1.2-3.8	2.5
	-1 hour	32	8 hour	0 - 17	NA	-STEL	400 ppm	Kitchens 30.5-120	- -		
	U.S.										
	-8 hour	9	1 hour	0 - 31	NA	MOL	35 ppm				
	-1 hour	25				-STEL	400 ppm				
Carbon Dioxide (CO_2)	NA	NA	1 hour	NA	400	ACGIH		1 hour 0-3000	NA	1.1-4.4	
						- 8 hour	5000				
						- STEL	15000				
						ASHRAE	2500				
						MOL(8 HR)*	600				600
Nitric Oxide (NO)	NA	NA	NA	NA	0.002	ACGIH		1 hr .030-0.30	0.50	NA	0.5
						- 8 hour	25				
						STEL	35				
Nitrogen dioxide	Canada (Maximum acceptable)										
	-Annual	0.056	Annual	0.01-0.0	0.026	ACGIH					
	-24 hour	0.11	24 hour	NA	0.011	-8 hour	3.0	general 0.1-0.53	-	1 - 5	0.15
	-1 hour	0.220	1 hour	NA	0.530	-STEL	5.0	1 hour 0.05-0.50	0.90		
	-Calif(1 hr)	0.250				WHO					
	Colorado(1 hr)	0.100				-1 hr	0.10-0.17				
Formaldehyde	NA	NA	2 hour	0.01-0.05	NA	UFFI/ICC					
						-7 day	0.05	0.02-0.4	0.4	NA	0.05
						MOL Ceiling	1.0				
Radon	NA	NA	30 day	0.1-1.0 pCi/L	NA						
						AECB		0.1-1140 pCi/L	?	NA	5 pCi/L
						-Prompt Action 50 pCi/L					
						-Criterion 7 pCi/L					
						-Investigate 3 pCi/L					

* MOL guideline for CO_2 concentration in office buildings (see discussion in Appendix 2)
for industrial exposure CO_2 vaue is the same as the ACGIH 8 hour value.

typical urban areas. As discussed in Appendix 2, the Canadian NAPS program measures ambient air quality levels in some urban environments in Canada, but no data are available for the Cambridge area. Some data were collected on outdoor air quality levels in this study. The ratio of indoor levels to outdoor levels is sometimes used to judge the acceptability of indoor air quality. The data generated by Yocom (1982) is a good reference point for any discussion of indoor/outdoor air quality ratios. As with the previous subjects in this chapter, the indoor/outdoor ratios reported in the literature are summarized in Table 4.1. Details of I/O ratios from various studies are contained in Appendix 2. Since such ratios are highly sensitive to the sampling location, i.e., in downtown areas outdoor levels are higher, these will not be used in this study.

Both standards and reported levels can be used to put the Cambridge study into perspective. Unfortunately, outdoor standards are not reliable indicators of what indoor air quality levels should be. Humans tend to spend much more time indoors than we do outdoors, particularly in the Canadian environment, and thus indoor air quality levels should potentially be lower than outdoor levels to guard health.

Similarly, the use of industrial hygiene (workplace) limits to set residential air quality standards is not considered a good practice. Industrial hygiene standards are set on the basis of an 8-hour worker exposure to these particular contaminants followed by a 16-hour period where the worker is not exposed. There are some recovery mechanisms present that will allow people to fend off the health effects of exposure to contaminants, if they are allowed a period of time away from the contaminants. A second important limitation is that workplace standards assume healthy adults (18-65) rather than typical household residents (children). As is discussed in Appendix 2, for certain pollutants the scientific community does not have sufficient data to allow it to state of what the chronic or long-term exposure effects are from exposures to low levels of air pollutants.

Some precedent exists for utilizing industrial hygiene values as a starting point for the selection of appropriate standards for indoor air quality. In 1981, the Canadian federal government, through its agencies, the National Research Council and the UFFI Information and Coordination Centre, established an appropriate level for formaldehyde gas concentrations in UFFI insulated homes. In establishing this level, they took 1/20th of the currently adopted ACGIH TLV for formaldehyde. The ACGIH value is set at 1.0 ppm and thus the criteria level set by UFFI/ICC was 0.05 ppm, or 50 ppb, formaldehyde gas in homes.

On the basis of the UFFI/ICC precedent, the authors have selected an action level for each pollutant measured in this study. This action level will be utilized as the cut-off below which discussion on results of the monitoring programs will be limited to comparisons between different types of houses and presentation of the house results. Above this action level, consideration will be given to the appropriate remedial measures that may be instituted by the homeowners. The setting of a action level does not indicate that harm will necessarily occur to the health of the occupants at the higher levels. Rather, it is a cautious approach in light of the absence of long-term dose response information. The final column of Table 4.1 provides the action level designated for this study. The action level set for carbon monoxide, nitrogen dioxide and formaldehyde are based on 1/20th of the industrial hygiene standard in the absence of other data. No further discussion of these substances with respect to their action level will be undertaken at this time. The other three contaminants shown on Table 4.1 have action levels that do not correspond to 1/20th of the industrial hygiene TLV. These are discussed below.

Carbon Dioxide

As can be seen from Table 4.1, average reported levels of CO_2 in urban centres tend to range as high as 400 ppm. The 8-hour TLV for carbon dioxide is set at 5,000 ppm and, if one were to take the 1/20th action rule, to establish a action level for this study, one would have a level of 250 ppm. Clearly, with average ambient levels reported as high as 400 ppm, it was considered somewhat inappropriate to take such a low action level for this study. Based on the information discussed in Appendix 2 and provided by the Ontario Ministry of Labour, a value of 600 ppm was set as the action level for CO_2 in this study. This is less than the American Society of Heating, Refrigerating and Air Conditioning Engineers standard of 2,500 ppm. The Ontario Ministry of Labour is recommending that levels in excess of 600 be studied to see whether they can be lowered. This value was selected as an action level for CO_2 in this study.

Nitric Oxide

Nitric oxide has a significantly lower human toxicity than does nitrogen dioxide. Data reports that its toxicity is approximately five times less from that of nitrogen dioxide. The TLV worker exposure numbers of 25 ppm for NO and 3 ppm for NO_2 would tend to

corroborate this information. There would thus be some justification for selecting an action level for this study that is between 0.75 and 1.25. However, reported maximum levels of NO in homes are only 0.5 ppm and this was selected as the action level for the Cambridge study. While this value may be low, it is considered to be more representative of potential situations that occur in the homes.

Radon

As discussed in Appendix 2, the AECB has set three levels as cut-offs for various actions concerning radon in homes. These correspond to 0.15 WL, 0.02 WL, 0.01 WL. Using an equilibrium factor of 0.3 the AECB state that the approximate radon concentration equivalents are 50, 7 and 3 pCi/L respectively. Given that no information was collected during the preliminary part of this study on equilibrium factors in the study homes, the authors conservatively selected an equilibrium value of 0.4 to develop the action level for this study. Whereas AECB has selected a radon concentration of 7 pCi/L as being the primary standard by which they will judge all indoor radon levels, the authors of this report recommend the value of 5 pCi/L be introduced as the selected radon action level. Since it is anticipated that the equilibrium factor in the Cambridge homes may be somewhat in excess of that found in the Elliot Lake homes, this lower action level is considered more appropriate for energy efficient homes.

4.3 Consideration of Measured Results

4.3.1 Testing Dates and Meteorological Conditions

Testing was undertaken during the latter part of March and the latter part of April. Initial screening tests commenced March 21, 1983 and ran until April 4, 1983 excluding Sunday, March 27 and the Easter weekend April 1-3, 1983. Climate data collected at each house and barometric pressure, wind speed, and wind direction from Waterloo Wellington Airport are summarized in Table 4.2.

Table 4.3 provides the relevant climate data for the week of combustion testing (April 19 - April 23, 1983).

Table 4.2: AVERAGE OUTDOOR CLIMATOLOGICAL CONDITIONS PHASE A STUDY

Date	House Tested Morning	House Tested Afternoon	Relative Humidity 6 a.m. - 4 p.m. % Range	Temperature (°C) Morning	Temperature (°C) Afternoon	Barometric Pressure (mbar)	Wind Speed (km/hr)	Direction
21.03.83	44	50	89-83	-8.0	-7.0	979.1	38	W
22.03.83	31	36	82-76	-4.5	-5.0	968.5	15 - 20	W
23.03.83	34	45	76-65	-5.0	-1.5	965.8	15 - 28	W
24.03.83	48	33	82-45	-5.0	-3.0	982.9	11	N
25.03.83	40	42	62-37	-2.5	-1.0	982.2	4	N
26.03.83	32		77-28	8.0		999.8	7	SE
28.03.83	47	43	100-87	3.0	4.0	966.9	9	SW
29.03.83	38	37	73-57	-1.5	-1.0	988.7	13	N
30.03.83	49	41	85-41	6.0	6.0	988.2		Calm
31.03.83	46	35	78-40	7.0	8.0	978.0	15	E
04.04.83	39		94-72	4.5		982.8	4	S

Table 4.3: AVERAGE OUTDOOR CLIMATOLOGICAL CONDITIONS PHASE B STUDY

Date	Houses Tested		Daytime[1] Temperature (°C)	Relative Humidity (% Range)	Barometric Pressure (mbar)	Wind Speed (km/hr)	Direction
19.04.83	42	49	0	90-46	1008.5	10	NW
20.04.83	47	50	1	77-56	1004.4	25 38	NW
21.04.83	32	35	5	78-39	1005.7	22	N
22.04.83	48	31	9	91-53	1013.9	5	NW
23.04.83	44		10	91-35	1012.9	4	S

1 Obtained from minimum and maximum recorded temperatures

4.3.2 Questionnaire Results

Not all the data collected on the questionnaire is directly applicable to consideration of indoor air quality issues. A selected analysis of the questionnaires was therefore undertaken for this study. Structural data is presented in Appendix 1 (type of construction, type of heating system, number of storeys and age). Air flow data on the house is contained in Table 4.4 (number of fans and fireplaces, disposition of dryer vent, and type of water heater). All homes were single detached dwellings. They were divided into age range categories (pre 1920, 1920-1945, 1945-1960, 1961-1970, and post 1970) by the MMAH. The balance of the data dwelling details and occupant habits are provided in Table 4.5.

Garage data, information on the fireplace and the number of plants in the house are the traditional dwelling details in Table 4.5. Attached garages, particularly with direct access to the house can influence indoor air quality. The type of fireplace, open or enclosed, gas, wood or woodstove produce different operating conditions. None of the six houses with operating fireplaces supply air directly to the firebox area, thus all combustion and exhaust air comes from the dwelling.

Under the miscellaneous category, information about the number of plants inside the house is not analysed. Most houses have some plants. Only one house has a fish aquarium (46), but it is a closed tank and shouldn't greatly influence humidity levels. Only house 44 and house 39 had air purifiers. In house 39 the unit in the living room is only used in the evening. In house 44 the unit is in the kitchen.

Occupancy data includes the number of people in the house and the number of smokers. Water use information deals with the potential to generate moisture in the house. Questionnaire answers not summarized include the number of baths, only house 34 had more than one bathtub; and the type of washing machine, all had automatic units, except house 41 whose washer had been out of commission since January. Except for houses 44 and 50 all houses used electric stoves, these two exceptions use gas. Use of stoves is reported on a scale of 1 to 5 ranging from not used to most often used.

Table 4.4: HOUSE INFILTRATION RATES AND EXHAUST CAPACITY

House	Heating Type	Infiltration Rates Air Changes/Hour		# Fans	Fireplaces	Gas WH Yes/No	Dryer Exhausted Inside/Outside	Furnijet Installed
		Initial Test	Second Test					
31	Forced Oil	0.15	0.23	2	1	N	Out	Y
32	Forced Gas	0.60	0.39	1	0	Y	In	N
33	Electric	0.0	-	1	1**	N	In	NA
34	Forced Gas	1.92	-	1	0	Y	Out	N
35	Forced Oil	0.38	0.24	0	1	N	Out	
36	Forced Gas	0.38	-	1	0	Y	In	N
37	Electric	0.52	-	1	0	N	Out	NA
38	Electric	0.52	-	0	0	N	Out	NA
39	Forced Oil	0.66	-	0	0	N	NA	
40	Forced Gas	1.32	-	0	1	N	Out	N
41	Electric	0.78	-	1	0	N	NA	NA
42	Forced Gas	1.68	1.08	2	0	Y	Out	Y
43	Forced Gas	-0.42*	-	0	0	N	NA	N
44	Gravity Gas	0.04	0.36	0	0	N	Out	N
45	Forced Gas	0.55	-	1	0	Y	Out	N
46	Electric	0.58	-	1	(W)	N	Out	NA
47	Forced Gas	0.22	0.37	2	1	N	Out	N
48	Forced Oil	0.72	0.18	0	2	N	Out	N
49	Forced Gas	0.16*	0.11	2	0	Y	Out	Y
50	Forced Gas	$1x10^{-11}$	0.48	0	0	Y	Out	N

* Rate Values calculated from two measurements
** Closed off
W Wood Stove

TABLE 4.5: QUESTIONNAIRE RESULTS

	DWELLING DETAILS								OCCUPANCY DETAILS																			
		Garage			Fireplace Details				Number								Water Use							Cooking Use (1 - not used) (5 - most used)				
House Number	Yes/No	Attached Y/N	Size	Door to House Y/N	Number	Type Open/Enc.	Glass Doors	Number Indoor Plants	Adults	Children	Smokers	Home During Day	Smokers Home	Humidifier	Combustion Air	Number Sinks	Y/N Showers	Y/N Dishwasher	Frequency Wash	Water Consumption (m^3)	Detergent	Bleach	Fabric Softener	Fry	Broil	Bake	Microwave	Other
31	N	-	-	-	1	0	Y	15	2	0	0	2	0	N	F	5	1	N	4	17	Y	Y	D	1	0	5	2	-
32	Y	Y	1	N	0	-	-	15	2	2	0	2	0	D	N	4	1	N	2	28	Y	N	W	1	0	1	0	5[B]
33	Y	N	1	-	1	-	-	3	1	0	0	3[B]	0	N	N	4	1	N	1/2	6	Y	N	W	5	0	1	0	T.O.
34	N	-	-	-	0	-	-	3	2	4	0	1	0	N	N	6	1	N	4	52	Y	N	W	5	0	3	0	-
35	Y	N	2	-	1	-	N	0	1	0	1	1	1	D	N	5	1	N	1/2	14	Y	N	D	0	1	4	0	-
36	Y	N	1	-	0	-	-	0	2	0	0	2	0	N	N	4	1	Y	1	31	Y	Y	W	2	1	5	0	-
37	N	-	-	-	0	-	-	10	2	1	0	2	0	N	N	4	1	N	3	26	Y	N	-	5	1	3	0	-
38	N	-	-	-	0	-	-	-	2	2	1	3	-	R	N	5	1	N	7	29	Y	Y	D	5	0	3	0	-
39	N	-	-	-	0	-	-	10	1	0	0	0	0	P	N	3	0	N	1	7	Y	N	W	5	0	4	0	T.O.
40	Y	N	1	-	1	G	Y	10	2	0	0	2	0	N	N	3	1	N	1	16	Y	N	W	1	2	4	0	-
41	Y	Y	1	N	0	-	-	20	2	3	1	2	0	N	N	5	1	N	0	20	NA	NA	NA	5	1	3	0	-
42	N	-	-	-	0	-	-	10	2	2	2	0	0	D	F	5	1	Y	7	NA	Y	Y	D	5	0	3	0	-
43	Y	Y	1	Y	0	-	-	0	2	0	0	2	0	D	Y	5	2	N	1	13	Y	Y	W	2	1	5	0	-
44	Y	N	1	-	0	-	-	0	1	0	1	1	1	N	N	2	0	N	1/2	5	Y	N	W	5	0	4	0	-
45	N	-	-	-	0	-	-	23	2	0	1	0	0	P	N	3	1	Y	1	NA	Y	Y	W	1	5	2	0	R
46	Y	Y	1	Y	1	WS	-	10	2	2	1	0	0	N	N	4	1	Y	3	34	Y	Y	D	5	0	1	0	-
47	Y	Y	1	Y	1	0	N	20	2	0	1	2	1	D	N	6	1	N	1	14	Y	Y	D	5	0	2	0	T.O.
48	Y	N	2	-	2	0	Y	5	3	0	0	2	0	N	N	4	1	N	1	24	Y	Y	W	1	1	5	0	-
49	Y	Y	1	N	0	0	N	15	2	2	0	1	0	N	F	4	1	N	2	40	Y	Y	D	2	4	5	0	-
50	N	-	-	-	0	-	-	10	2	0	0	2	0	D	N	4	1	Y	2	25	Y	N	W	2	0	5	0	-

G - Gas
WS - Wood Stove
B - Babysits during day

D - Drum
P - Plate
R - Room

Y - Yes
N - No
F - furnijet

D - Dryer
W - Washer
NA - not applicable

B - Boiling
T.O.-Toaster Oven
R - Rarely at Home

4.3.3 Detailed Review by Pollutant

Introduction

Having selected an action level by which one can separate homes with higher indoor air quality levels from the general trends, it is appropriate to review the results of the measurement program as shown in Tables 4.6 to 4.9. These tables show both indoor and outdoor levels. The outdoor levels will be considered with respect to reported levels in Canada and standards, whereas the indoor levels will be compared to the action level developed in the preceding section.

A number of considerations must be recognized in reviewing the data. The results reported in the tables generally show themselves to be in two ranges: below the detection limit and a number expressed as an absolute concentration in ppm. The numbers are expressed this way due to the imposition of a detection limit, below which one cannot place a great deal of confidence in the absolute value measured.

It should also be considered that while only one measurement was made outdoors, three measurements were commonly made inside the houses. While it would be convenient to average indoor data, particularly for the purposes of comparing levels indoors to standards, this may not be the most appropriate procedure. Carbon dioxide, and formaldehyde results are presented with a house average for each set of measurements. When one considers the results shown in Tables 4.6-4.8, it is readily noticeable that in many cases, only one value in the house is significantly higher than the others. Under these circumstances that value tends to dominate the house average and provides a distorted view of the level of that pollutant in the house. This is particularly noticeable for carbon dioxide and will be discussed later. It is therefore important that one considers all the data for a particular house and attempts to explain why levels may be high in given regions and low in others.

Carbon Monoxide

Reviewing the carbon monoxide data collected during this study, Table 4.6, shows that outdoor measurements are at the low end of the range reported in Table 4.1. All of the 20 homes surveyed had outdoor carbon monoxide concentrations that were less than 2

ppm, the detection limit. This result is not surprising considering that most of the homes are located away from major traffic routes and therefore not subject to carbon monoxide contamination from automobiles. Automobiles tend to provide the highest level of carbon monoxide contamination to the urban environment (Barton, 1981). Low levels measured outside the Cambridge houses indicates low traffic volumes in the area.

Consideration of the indoor carbon monoxide levels shown in Table 4.6 shows that only two readings were in excess of the 2.5 ppm selected action level for this study. Homes 43 and 44 each reported a reading of carbon monoxide of 3 ppm. Only three other levels of carbon monoxide were recorded above the detection limit. Each of these levels were recorded in different houses and the levels reported is 2 ppm in each case.

House 43 is a one and one half storey, wood frame home, with gas forced air heating. It does not have a gas water heater nor are there any exhaust fans in the building. Air exchange rates for this particular house were calculated to be -0.42 ACH on the basis of only two measurement points. This implies some problems with the measurment. Short circuiting may be occurring. Given the higher level of CO recorded in the basement, and this air exchange rate no immediate action is considered necessary, however, the operation of the furnace should be examined.

House No. 44 is two storey, wood frame home, built between 1920 and 1945. The house has a gravity gas fired furnace and cooking is undertaken on a gas range. It is noted in Table 4.5 that the occupant of the home smokes and also does a significant amount of frying on top of the range. The air exchange rate for this house was measured on two occasions. The first occasion showed a very low value, the second occasion produced a value of 0.36 ACH. Smoking and gas fired appliances are noted in Appendix 2 to be a major contributor to carbon monoxide in the indoor environment. It is quite likely that, with the low air exchange rate in this home, the gas stove is the source of the carbon monoxide noted. This supposition is further reinforced by the fact that the highest levels were recorded in the kitchen.

Carbon Dioxide

Again referring to Table 4.6, it can be seen that only five of the twenty homes had reported outside carbon dioxide values in excess of the detection limit of the method.

Table 4.6: MEASURED CO and CO_2 CONCENTRATIONS (ppm)

House Number	Outside CO	Outside CO_2	Basement CO	Basement CO_2	Main Floor CO	Main Floor CO_2	Bedroom CO	Bedroom CO_2	House Average CO_2
31	-	-	-	390	-	3400^{K**}	-	340	1400
32	-	-	-	1600	-	1500^{LR}	-	250	1100
33	-	-	-	-	-	3400^{LR**}	-	1100	2300
34	-	390	-	1300	-	420^{D}	-	340	670
35	-	-	-	-	-	-	-	-	-
36	-	-	-	430	-	2500^{DR}	-	410	1100
37	-	-	-	-	-	800^{LR}	-	630	490
38	-	-	-	-	-	260^{LR}	-	420	270
39	-	-	-	-	-	-	-	-	-
40	-	580	-	-	-	380^{D}	-	-	230
41	-	-	-	-	-	-	-	-	-
42	-	-	-	-	-	-	-	1500	1500
43	-	610	3	340	-	350^{LR}	-	350	350
44	-	-	-	NA	3	3700^{K*}	-	420	2100
45	-	-	-	2700	-	1300^{K}	-	220	1400
46	-	-	2	-	-	300^{LR}	-	210	180
47	-	400	-	420	-	2800^{D}	-	430	1200
48	-	350	-	-	-	420^{LR}	-	340	290
49	-	-	-	-	2	210^{LR}	-	250	-
50	-	-	-	-	2	420^{K}	-	-	240

NA Not Available
\- Less than detection limit (2 ppm CO and 200 ppm CO_2)
Area: K Kitchen
LR Living room
D Den
DR Dining room
F TV Room (family room)
* Pump shut off after 1.5 hours sampling
** Pump shut off after 1.25 hours sampling

The range of the five samples was 350 - 610 ppm with an average of approximately 470 ppm. With the balance of the samples having no detectable CO_2 concentration, it is evident that the outdoor CO_2 levels in Cambridge bracket the reported national average 400 ppm. With the major influence on CO_2 levels being large local combustion sources, this data is as one would expect it to be.

Indoor values of CO_2, however, show signficant differences from reported values. Fourteen values out a total of 59 samples taken, provided concentrations, over the testing period, in excess of the selected action level of 600 ppm. Considering the average values calculated for each of the houses, nine houses showed averages in excess of 600 ppm. These averages ranged from 670 ppm to 2300 ppm. It is important to note that in six of these nine cases, the house average was dominated by one reading in the house. Its effect on the overall average for that house was significant. Three houses with averages greater than 600 ppm had two values in excess of 600 ppm contributing to the overall average. This would tend to indicate that, in the latter cases, the averages more closely reflect the overall situation in the house.

The overall ranges in the homes, where values were recorded to be above the detection limit, was 210 to 3700 ppm. The highest levels were generally recorded in what was termed the main floor area. Referring back to Table 4.1 it will be noted that other studies reported one hour averages of CO_2 normally range from 0 to 3000 ppm. With an upper range in this study of 3700 ppm, we have a number of cases that should receive individual attention.

In order to explain some of the carbon dioxide numbers recorded in the homes it is necessary to consider the sources of carbon dioxide and the factors that influence its levels in the home. The sources are predominantly gas fired appliances and the human metabolism. Thus, as more people are in the house, the levels may tend to go up if insufficient air exchange rates are present. Employing more gas fired appliances may raise the levels in the house, particularly if they are unvented appliances such as ranges.

As one would expect, if the normal ventilation rate in the home is increased the level of CO_2 would decrease given a constant generation rate inside the house. NRC, 1969, reports that the standard human produces approximately 4% CO_2 in the exhaled air. If one assumed that standard man exhaled 1/2 m^3/hr, NRC suggests that one person could

add approximately 20 litres of CO_2 to the atmosphere of a given room in one hour. If air exchange is limited 1/2 m^3/hr, the level of CO_2 in the air would thus rise until it got to the 4% level. This level would be detrimental to human vitality. Such findings have been reported by others who have tested the effects of reduced ventilation rates on CO_2 levels in schools (Yocom, 1982). If one considers the results from the Howland House study (IEC BEAK, 1983a), one can note that in the basement the CO_2 level was recorded as 420 ppm, it rose to 830 ppm in the second floor office area and 1670 ppm in the main floor living room. During the period of the monitoring at Howland House, it was possible to accurately record the number of people in each area. Generally speaking there was one person in the basement during the testing, two people in the upstairs office and three to four people in the living room. Outside levels at Howland House are approximately 290 ppm, thus showing a slight rise between the outside and inside levels at this location. The results from Howland House again indicate that, given the house's very low air infiltration rate, there was a definite source and dilution relationship dominated by human metabolism inside the building. NRC suggest a minimum of 85 litres per minute of fresh air should be supplied for each person in an area. With 200 cu.ft. per person (5.7 m^3) and 3 cfm (85 Lpm) of fresh air steady state conditions of CO_2 occur in 3 hours. With 57 m^3 per person the volume would take 30 hours to reach equilibrium with 85 Lpm of fresh air.

The highest CO_2 level recorded during this study, 3700 ppm at house 44, was recorded in the kitchen. As stated earlier, House 44 is equipped with a gas fired range and the occupant does a significant amount of cooking. There is no localized exhaust from the kitchen, thus this high level of CO_2 is not surprising. Furthermore, during the testing period the homeowner spent the majority of the time in the kitchen, thus contributing metabolic CO_2 to the atmosphere.

Given the low air exchange rate measured in House 33, and the fact that four people were present in the house during the testing period, the source dilution relationship would explain one of the next highest CO_2 concentrations recorded in this study. While doubts exist as to the validity of the infiltration rate measurements in this house, the contaminant levels indicate low exchange rates. Low air exchange rates were also recorded for House 31, which, while it doesn't have a large occupancy, did record a 3400 ppm CO_2 concentration in the kitchen during the test program. Similarily limited

ventilation may be the cause of high levels in House 47, which recorded 2800 ppm CO_2 concentrations in the dining room.

House 47 has a low occupancy rate but it also has a low air infiltration rate. It was also noted, during the combustion test, that the stack draft pressure in House 47 became very erratic when all combustion and venting appliances were operating. It was noted that of the 10 houses recording levels in excess of 600 ppm, two were electric houses, one was heated with oil and the balance had gas furnaces. The critical nature of the gas furnace, with its atmospheric draft hood, was mentioned earlier. These units are susceptible to back drafts and such a situation could cause the CO_2 generated in the furnace to be emitted to the home environment should a negative pressure exist in the chimney. With the erratic behaviour in house 47, the high CO_2 concentrations could also be a function of this type of situation.

House 45 recorded two values in excess of 600 ppm, 2700 ppm in the basement and 1300 ppm in the kitchen. House 45 has a gas water heater, as well as a gas furnace but no explanation was readily apparent for the high levels in this house.

House 36 is also equipped with a gas water heater and gas furnace and recorded 2500 ppm in the dining room. The air change rate in this particular house is 0.38 ACH. It is most likely that the elevated level is a function of human metabolic activity and the low ventilation rate.

House 32 recorded two values in excess of 600 ppm for CO_2. In the basement, 1600 ppm CO_2 was recorded and 1500 ppm was measured in the living room. This house has a high occupancy rate and was tested in the morning. One would anticipate that the monitoring results show the residuals of morning activities in a household of 4 persons. The house is relatively well sealed with an air exchange rate measured during the combustion testing phase of this study at 0.39 ACH.

A similar residual effect is anticipated to have existed in House 34 which recorded a 1300 ppm CO_2 concentration in the basement. A slightly elevated level of 420 was recorded in the dining room of this home. Testing was again done in the morning in this house and six residents live in the house. With the relatively high ventilation rate recorded during the initial phase, 0.91 ACH, the occupants may all contribute to the

level of CO_2 measured even though the house is equipped with a gas water heater and a gas fired furnace.

House 42 has 4 occupants, a gas water heater, a gas furnace and an air exchange rate, measured during the second test, of 1.08 ACH. CO_2 levels of 1500 ppm in the bedroom were recorded during an afternoon test. No ready explanation is supplied for this particular case since it is noted in Table 4.5 that normally nobody is at home during the day. During the testing, the technician and 1 member of the family were in the house.

The final home considered in the testing program that had values in excess of 600 ppm CO_2 concentrations was House 37. These values were slightly elevated being 800 ppm in the living room and 630 ppm in the bedroom. This house is an electrically heated home with a calculated air exchange rate of 0.52 ACH. Three people are resident in this home which was again tested in the afternoon. One would anticipate that the results of the test show residuals from family activity in the home.

A final point should be considered before leaving the carbon dioxide monitored results. This is the situation of ineffective circulation in buildings. This may give rise to localized "hot spots" or levels with higher concentrations of air pollutants. It is evident from looking at the data in Table 4.6 that the majority of the high levels of carbon dioxide were recorded on the main floor. These values could be due to the concentration of occupancy on this floor, but, they could also be due, in some cases, to a lack of adequate circulation from some areas of the house. Three of the eight values recorded occurred in kitchens. The houses were not inspected for the presence of appropriate air circulation patterms.

Oxides of Nitrogen

The results of nitric oxide (NO) and nitrogen dioxide (NO_2) measurements are shown in Table 4.7. The selected action level for NO is 50 pphm (0.5 ppm); the level for NO_2 is 15 pphm (0.15 ppm).

Outside measurements of nitric oxide produce seven values less than the detection limit with the rest of the samples lying in the range of 3 to 8 pphm (0.03 to 0.08 ppm). The average for these values is 3.5 pphm (0.035 ppm) but it does not include the seven values

Table 4.7: MEASURED NO AND NO_2 CONCENTRATIONS (pphm)

House Number	Outside		Basement		Main Floor*		Bedroom	
	NO	NO_2	NO	NO_2	NO	NO_2	NO	NO_2
31	-	-	3	-	-	3	3	-
32	5	10	4	3	5	9	12	7
33	-	-	-	-	-	-	-	-
34	3	4	-	-	-	-	7	5
35	5	4	3	8	3	7	8	7
36	-	3	4	4	3	-	3	-
37	4	7	6	8	5	4	-	5
38	3	-	7	4	9	7	9	6
39	-	4	6	-	10	-	6	5
40	5	-	5	5	-	4	2	-
41	3	3	2	4	4	6	2	-
42	8	3	-	-	4	-	12	6
43	2	5	14	23	17	5	26	7
44	3	3	-	-	160	30	150	25
45	-	-	3	-	2	-	6	-
46	4	-	6	10	9	8	-	3
47	7	-	37	5	47	4	64	-
48	-	4	3	-	-	-	-	-
49	-	7	7	4	3	-	8	4
50	3	3	31	-	34	6	32	3

\- Less than detection limit (0.02 ppm NO and 0.03 ppm NO_2)

* Locations identical to those in Table 4.4

Note: pphm is parts per hundred million

1 pphm = 0.01 ppm

less than the detection limit. All these values would appear, however, to be higher than the reported outdoor level of nitric oxide of 0.2 pphm (0.002 ppm) shown on Table 4.1. It is noted in Appendix 2 that nitric oxide arises from bacterial action, particularly after rains. The higher levels in the Cambridge study may possibly be attributable to increased bacterial action in the wet spring of 1983, or to local sources of NO.

Nitric oxide readings inside the homes in Cambridge produced eleven values less than the detection limit of 0.2 pphm (0.002 ppm). Thirty-eight values were in the range of 2 to 9 pphm (0.02 to 0.09 ppm) and eleven values exceeded 10 pphm (0.10 ppm). Values that exceeded the action level set for this pollutant, 50 pphm (0.5 ppm), were recorded in House 44 and House 47.

House 44 recorded two values in excess of 50 pphm (0.5 ppm), 160 pphm (1.6 ppm) on the main floor (kitchen), and 150 pphm (1.5 ppm) in the bedroom. The value recorded in the basement of House 44 was less than the detection limit. Values in House 47 were from 37 pphm (0.37 ppm) in the basement to 47 pphm (0.47 ppm) on the main floor and 64 pphm (0.64 ppm) in the bedroom. This provides an average level for House 47 that is just below the selected action value. While house 47 does not fall into the same usage patterns as house 44 e.g., there is not gas stove in this house, it has been noted above that House 47 has high levels of CO_2. House 44, on the other hand, has a gas range and stove and it is quite likely that the high levels of nitric oxide recorded in this house arise from fuel combustion in the gas range. It is interesting to review the data and note that the next highest values for NO was House No. 50. House 50 is the only other house in the study that has a gas stove. There would appear to be a correlation between gas stoves and the high levels of NO in both house 44 and house 50.

Nitrogen dioxide readings outdoors, Table 4.7, produced seven values less than the detection limit of 3 pphm (0.03 ppm). The balance of the values were between 3 to 10 pphm (0.03 and 0.10 ppm) with an average of 4.6 pphm (0.046 ppm). Non urban levels tend to be at least an order of magnitude lower than the measured level (Robinson, 1970), however, the same author notes that urban areas can range from 10 times the non-urban level to 100 times the non-urban level. Cambridge is thus, from this limited study, in the range of recorded values for outdoor NO_2 concentrations.

Indoor measurements of NO_2 were conducted at all twenty homes in the Cambridge area. Using a selected action level of 15 pphm (0.15 ppm) only three values were recorded that exceeded this level. Twenty-five of the sixty measurements result in levels less than the detection limit of the methodology. The balance were in the range from 3 to 30 pphm (0.03 to 0.30 ppm) with an average value of 7 pphm (0.07 ppm). This 0.07 ppm value would appear to be generally below the ranges recorded in the literature and significantly below the selected action level for this study. The three values that were recorded as being above the selected action level were from House 44 with a 30 and 25 pphm (0.30 and 0.25 ppm), and House 43 with a 23 pphm (0.23 ppm) in the basement.

As discussed previously, House 44 has a gas range and the owner of the house smokes. Both these sources can give rise to NO_2 levels in the house and one would attribute the recorded level to these factors. House 43 recorded a high CO level in the basement as well as the high value of NO_2. As stated earlier, some doubt is raised, by these high levels in the basement, as to the adequacy of the ventilation rate testing undertaken in House 43. House 43 only has a gas furnace in the basement and it is possible that some problems exist with this gas furnace but these were not defined during this study.

Formaldehyde (HCHO)

Outside measurements of formaldehyde are reported in Table 4.8. These values range from 0.006 to 0.034 ppm and average 0.02 ppm. This data is significantly lower than the University of Western Ontario data collected in London. This fact should not be surprising since most of UWO's testing was undertaken on busy main city streets during rush hour. One source of formaldehyde is the products of combustion from gas fired engines and therefore one would expect to find these values slightly higher in London during rush hour than during the sampling in Cambridge.

Inside measurements of formaldehyde were compared to the UFFI/ICC action level of 0.05 ppm. This value was selected as 1/20 of the ACGIH Theshold Limit Value and was used to designate those houses were some means of remedial action was needed to cope with formaldehyde generation from urea formaldehyde foam insulation. Since formaldehyde is a ubiquitous substance in our environment, being in furniture, draperies, carpet, cigarette smoke, etc., it is not surprising to find six of the twenty houses had levels above the selected action level. Generally higher levels can be associated with

Table 4.8: FORMALDEHYDE TIME WEIGHTED AVERAGE

House	Outside Time (hrs)	Outside HCHO (ppb)	Main Floor[L] Time (hrs)	Main Floor[L] HCHO (ppb)	Second Floor[B] Time (hrs)	Second Floor[B] HCHO (ppb)	Indoor Average HCHO (ppb)
31	318.4	23	317.0	23	317.0	34	29
32	214.7	18	214.8	61	214.8	46[FR]	54
33	173.0	25	173.4	99	173.4	179	139
34	176.0	31	177.6	33[H]	177.7	27[D]	30
35	169.4	10	171.0	35	171.0	34	35
36	217.8	21	220.0	18	219.6	23[H]	21
37	164.4	17	164.6	65	163.9	71	68
38	167.5	25	168.0	57	167.7	56	57
39	NA[2]		168.3	35	168.1	40	38
40	151.6	25	153.4	11[DR]	153.0	19	15
41	NA[2]		162.2	36	162.2	35	36
42	236.3	24	245.9	42	245.9	42	42
43	166.0	6	166.5	25[DR]	166.5	23	24
44	202.4	15[1]	202.4	52	202.4	90	71
45	169.7	34	171.0	78	171.0	44	61
46	190.1	9	190.4	38	190.4	48	43
47	167.8	18	167.8	23[D]	167.7	19	21
48	177.8	27	178.1	17	178	18[H]	18
49	166.6	17	167.9	35	167.9	42	39
50	202.4	15[1]	197.4	13	197.4	15	14

FR Family Room
H Hall
D Den
DR Dining Room
L Living room unless noted
B Bedroom unless noted
1. Same dosimeter used for both houses (houses side-by-side)
2. NA not available, dosimeter broken
1000.0 ppb = 1.0 ppm

one of the previous sources or a lack of ventilation air in the house. With the sealing of the Cambridge houses, it is quite likely that the ventilation rates are below the level needed to remove any formaldehyde generated in that environment. Caution should be exercised however, in jumping to conclusions about the formaldehyde levels. The particular sampling apparatus used is subject to some interferences from other chemicals.

The overall average for the twenty houses on the main floor was 0.04 ppm and on the second floor, 0.045 ppm. The values range from a low of 0.011 ppm to a high of 0.179 ppm. Generally speaking the six houses where higher levels were recorded, lie in the low end of the range found in UFFI houses. All houses that recorded values of formaldehyde in excess of the action level had air exchange rates less than 0.60 ACH. Three of the six houses had smokers in them, Houses 38, 40 and 45. Three of the houses had gas fired appliances (32, 44 and 45), one had a gas range, House 44. The other three houses had electric heating.

The highest levels were recorded in House 33. It was determined by the field technician, that new kitchen cupboards had been installed in this house recently. It is possible that that these cupboards are releasing formaldehyde gas from the resins used to manufacture the particle board in the cupboards. The situation can be alleviated by supplying some fresh air to the house and after a period of 16 to 18 months, most of the free formaldehyde will have been released from the cupboards. At that time the values should return to normal levels.

The next highest readings of formaldehyde were recorded in House 44. As mentioned earlier the owner has a gas range and is a smoker. The owner undertakes a considerable amount of cooking and baking. Both gas range operation and smoking can give rise to high levels of formaldehyde in the home.

Similar comments about smoking and baking and broiling, which are prone to give off interfering substances can be made about House 45, House 37 and House 38. None of these houses have gas ranges, however, two of the houses have smokers and one of them does an extensive amount of frying.

The final house with high readings is House 32. There is no readily available explanation for the source of the formaldehyde in this house, however, the air exchange rate is measured at between 0.06 and 0.49 ACH and may contribute to elevated levels of formaldehyde in the house.

Radon

Outside measurements of radon taken during this study are shown in Table 4.9. They range from 0.05 pCi/L to 0.28 pCi/L. These values tend to be at the lower end of the range specified as being commonly found in the environment. They would tend to indicate no large sources of radium bearing material are present in the area.

It is thus rather interesting to note the apparent anomalies that turn up in the indoor measurements shown in Table 4.9. With exposure times ranging from 28 to 40 days, radon concentrations in the basements of the twenty houses were reported to be in the range 0.36 to 15 pCi/L. A selected action level of 5 pCi/L was developed for this study and while the concentrations in the houses would appear to be at the low end of the reported indoor levels, three values were recorded as being in excess of the selected action level. It is appropriate to consider a number of issues including the selected action level for this study.

If one selects the investigative level specified by AECB of 3 pCi/L a total of seven houses in this study were measured at levels that would indicate the need for further study. These are House 42 (3.0 pCi/L), House 41 (3.8 pCi/L), House 38 (3.9 pCi/L), House 36 (3.6 pCi/L), House 39 (5.4 pCi/L), House 40 (10 pCi/L), and House 37 (15 pCi/L). One additional house is borderline on the 3.0 pCi/L cutoff and that is House 33 at 2.9 pCi/L. Taking the selected action level for this study at least three houses require further work. Two houses are actually above the primary criterion level set by the AECB of 7 pCi/L.

As is discussed in Appendix 2, the arbitrary establishment of the 50, 7 and 3 pCi/L investigative levels in AECB (1977) is in some doubt for energy efficient homes. Kusuda (1980) presented the variations in equilibrium factor with various ventilation rates. From this information one would presume that the effective working level concentrations in many of the houses in Cambridge could be significantly above the AECB levels since the

Table 4.9: RADON EXPOSURE DATA

House	Outside		Inside	
	Concentration (pCi/L)	Relative Std Dev. (%)	Concentration (pCi/L)	Realtive Std Dev. (%)
31			1.2	15
32	0.12	55	0.62	22
33	0.13	40	2.9	8.0
34			0.96	17
35			1.3	17
36	0.18	40	3.6	8.4
37	0.13	55	15	4.7
38			3.9	9.1
39	0.13	49	5.4	6.8
40			10	5.2
41			3.8	10
42			3.0	9.8
43	0.07	85	0.76	22
44	0.05[2]	85	1.0	15
45	0.11	44	0.65	17
46	0.20	49	0.36	35
47			1.7	14
48			1.9	12
49	0.28	40	1.7	15
50	0.05[2]	85	1.8	12

1 Calculated as described in Reference Alter (1981)

2 Houses side by side same device.

air exchange rates are lower than normally assumed. Table 4.4 presents the house infiltration rates or air exchange rates per hour as measured during this study. It is noted that they range from a measured value of approximately 0.11 ACH to a value of 1.92 ACH excluding Houses 33 and 43. Using this information and interpolating from the Kusuda (1980) data as outlined in Appendix 2, it is possible to calculate an estimated working level concentration for the houses in Cambridge. The results of such a calculation are shown in Table 4.10. With the revised equilibrium factors of the eight houses discussed previously, seven houses appear to be above the 0.02 working level standard set by AECB. This interpretation is based on short-term air exchange rate data coupled with one month radon measurements. The standard is based upon annual average WL or radon daughters. Thus, any conclusions from the study must be tempered by the limited data. It is, however, obvious from Table 4.10 that consideration must be given to the sources and potential remedial measures to be taken in the houses recording working levels in excess of 0.02 WL, and especially houses 39, 40 and 37.

A further analysis of the radon results was undertaken to determine the distribution of the radon concentrations within the households and from the knowledge of the distribution determine the following:

- Do the measurements appear to all belong to the same general population and if not, to identify any outliers?
- What percentage of the houses appear to fall above regulatory guidelines?

Results which are rate dependent tend to follow a log normal distribution (King, 1971). This distribution should therefore hold for the levels of radioactivity in the environment and specifically for indoor radon concentrations. Other investigators (George et al, 1982, McGregor et al, 1980) have used the lognormal distributions to analyse their radon concentration measurements. The techniques to analyse lognormal distributions are described in the references of King (1971) and Aitchison and Brown (1957). The radon concentrations are plotted in Figure 4.1. From this figure we may observe that:

- The values may be described adequately by a single lognormal distribution
- All the values fall within the 95% confidence intervals, however, the values of 10 and 15 pCi/L measured in the basements of houses #40 and #37 respectively tend to lie at the fringe of the 95% envelope.

TABLE 4.10: RADON LEVELS AND CALCULATED WL

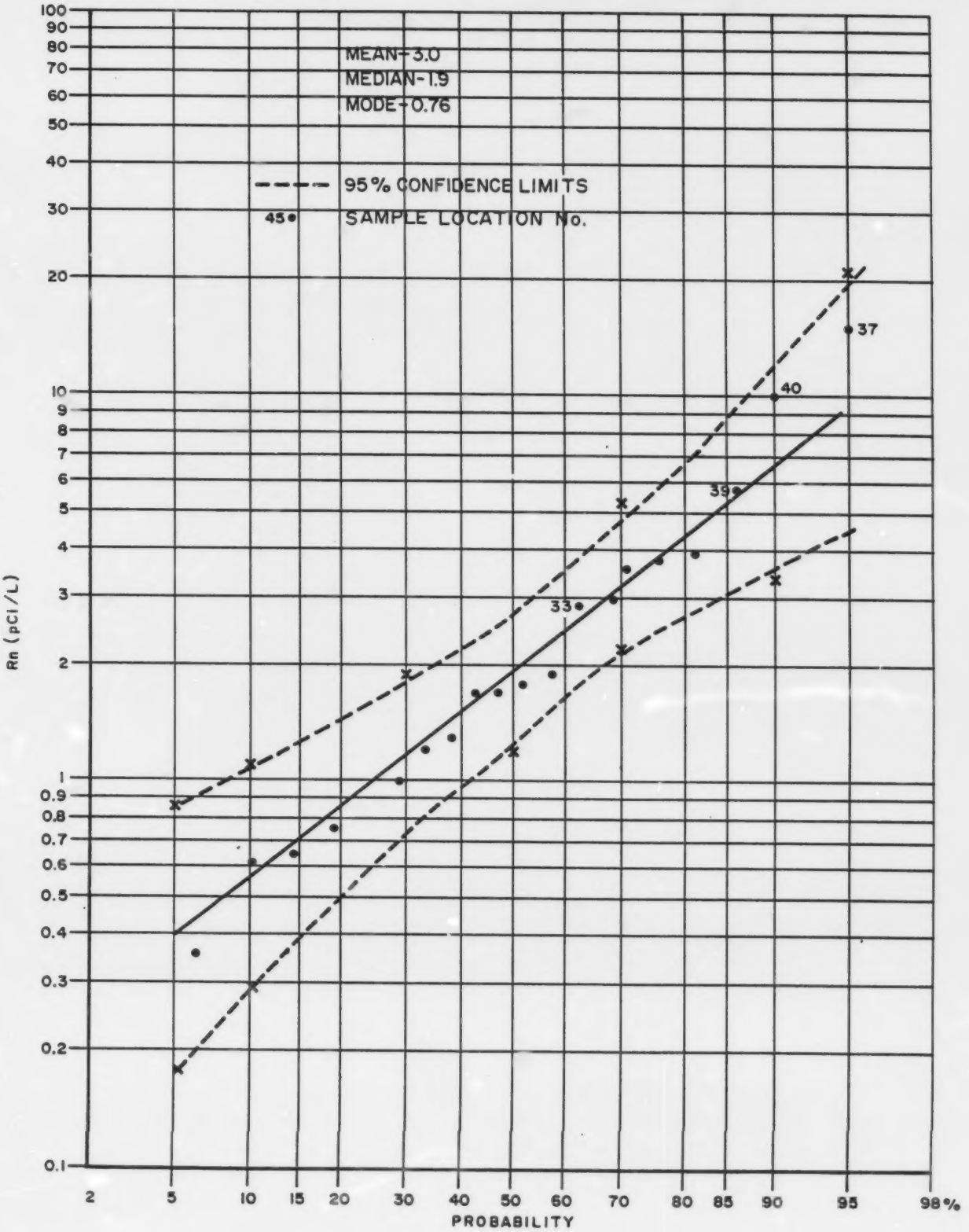
House	Air Changes/ Hour	F* (est)	Radon (pCi/L)	WL
46	0.58	0.70	0.36	2.5×10^{-3}
32	0.39	0.75	.62	4.7×10^{-3}
45	0.55	0.70	.65	4.6×10^{-3}
43	0.42***	0.75	.76	5.7×10^{-3}
34	1.92	0.51	.96	4.9×10^{-3}
44	0.36	0.75	1.01	7.6×10^{-3}
31	0.23	0.81	1.16	9.4×10^{-3}
35	0.39	0.75	1.29	9.7×10^{-3}
47	0.37	0.75	1.70	1.3×10^{-2}
49	0.11	0.9	1.71	1.5×10^{-2}
50	0.48	0.73	1.77	1.3×10^{-2}
48	0.18	0.9	1.95	1.8×10^{-2}
33	0.0***	1.0	2.93	2.9×10^{-2}**
42	1.1	0.6	3.02	1.8×10^{-2}
36	0.38	0.75	3.63	2.7×10^{-2}**
41	0.78	0.61	3.76	2.3×10^{-2}**
38	0.52	0.73	3.89	2.8×10^{-2}**
39	0.66	0.68	5.40	3.7×10^{-2}**
40	1.32	0.57	10.45	6.0×10^{-2}**
37	0.52	0.73	15.37	11.2×10^{-2}**

* Interpolated from Kusuda et al (1980).

** Values of calculated WL in excess of AECB (1977) criteria (0.02 WL)

*** Infiltration rates are suspect.

FIGURE 4.1 Distribution of Radon Data



From Figure 4.1 it can be deduced that the following relationships hold:

Level (pCi/L)	Probability of Exceeding Given Level
3	33%
7	9%
50	1%

From these results we can deduce that approximately 9% (or 2 in 20) of the houses will yield measurements that exceed the A.E.C.B. radon concentration standard.

Nero (1983) has stated that the radon concentration may as a first approximation be a function only of the rate of radon generation in a given volume and the ventilation rate. A plot of radon concentration versus the rate of air changes (Figure 4.2) fails to identify any particular trend. However, a distribution plot (Figure 4.3) of the volumetric radon source terms calculated by multiplying the radon concentration by the ventilation rate demonstrates that two lognormal distributions are required to adequately describe the values. This indicates that the sources of radon fall into two general groupings. The differences may be due to measurement errors such as the measurement of the ventilation rate. Otherwise, one would conclude that there are significant differences between the two groups of houses.

From this analysis it is appropriate to recommend that:

1. Radon measurements in houses #40, 37, 39 and 3 others be repeated to determine the consistency of the radon measurements. The living quarters of houses #40 and #37 should be monitored in addition to the basement to assess the potential problems.

2. Radon daughter levels in houses #40, 37, 39 and one other should be assessed to determine if significant problems exist and to determine appropriate values of the equilibrium factor for future interpretation of radon concentration data in these homes.

FIGURE 4.2 Radon Concentrations vs. Air Change Rate

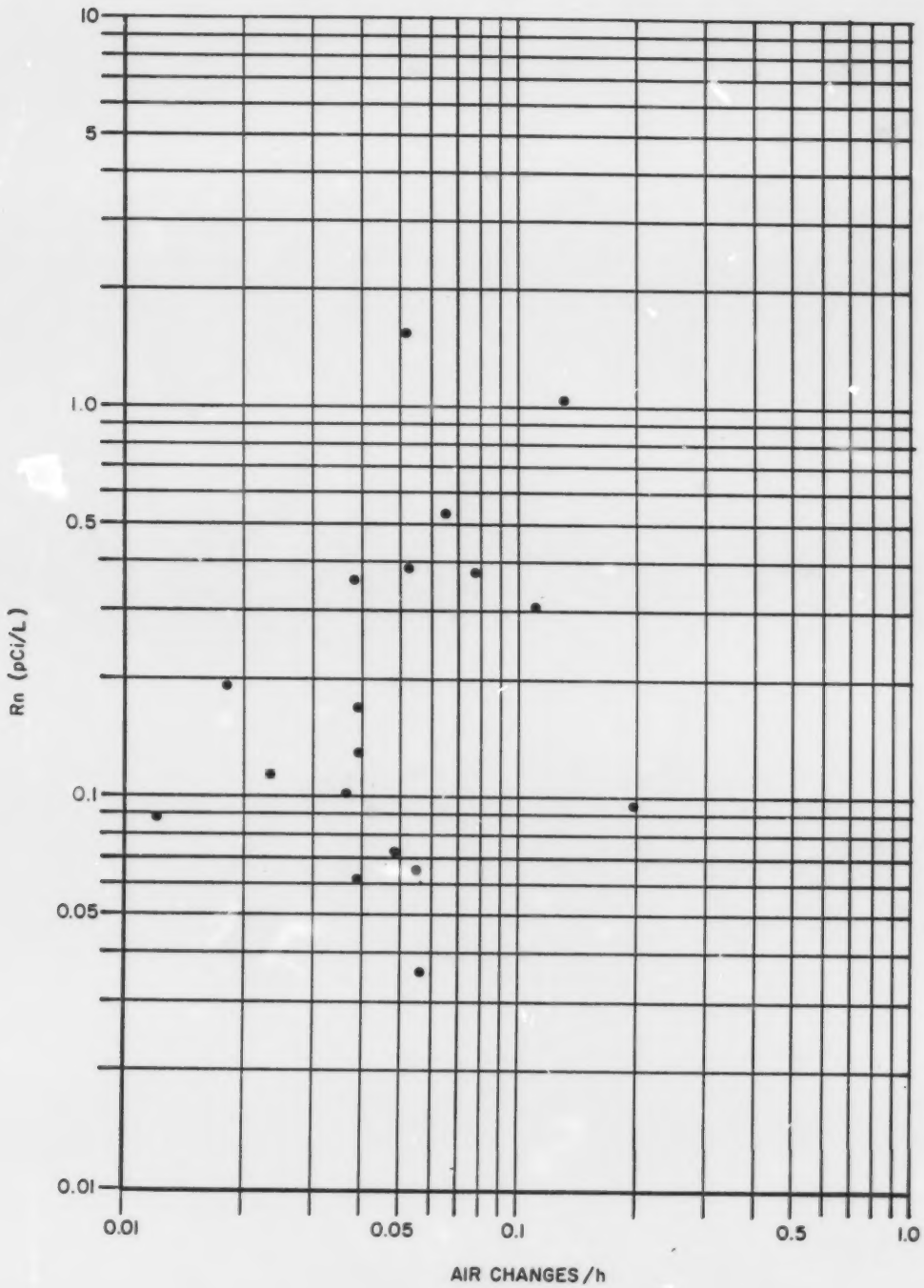
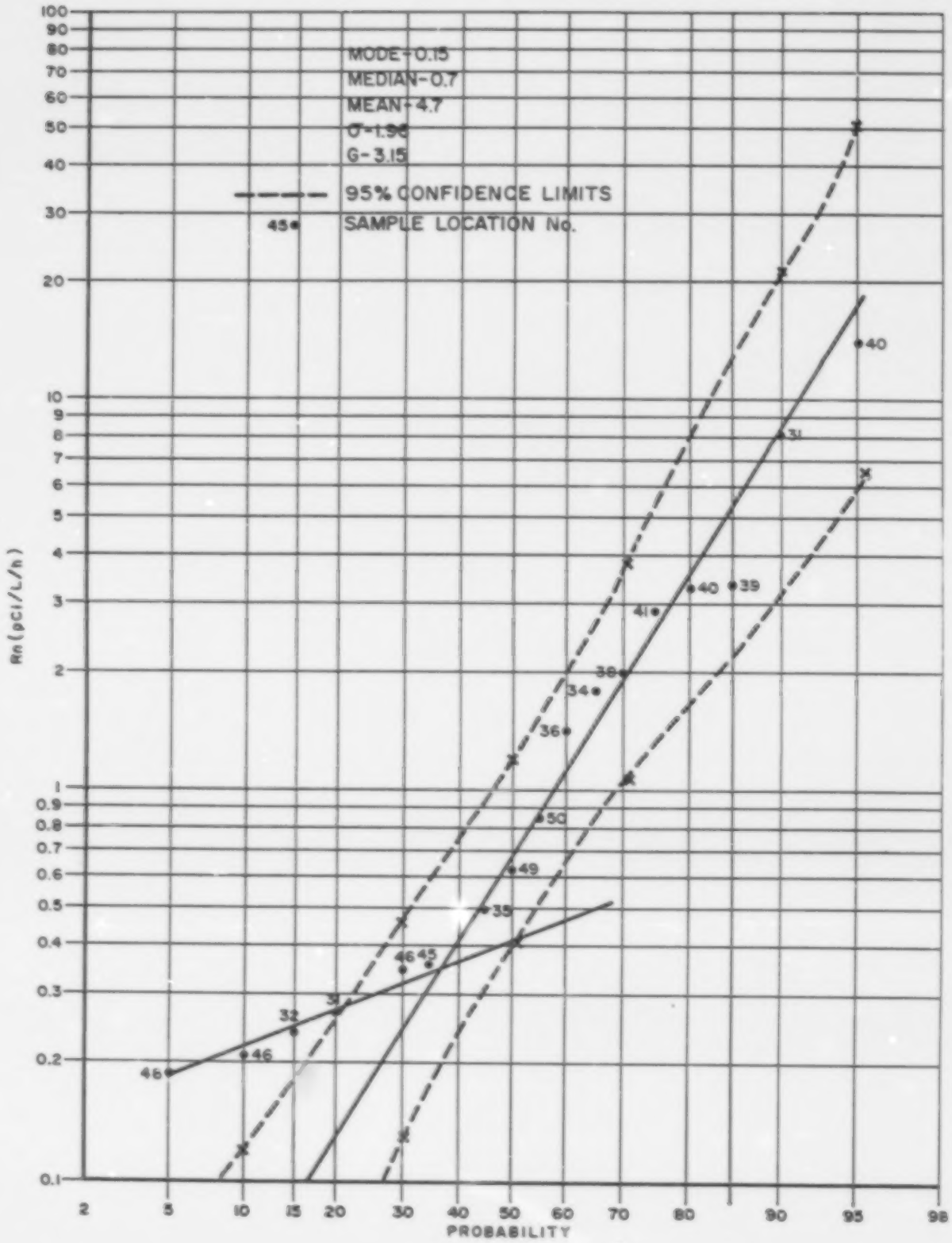


FIGURE 4.3 Rn Source Terms (pCi/L/h)



3. If high radon or radon daughter levels are confirmed, then the reasons for the high concentrations should be determined. Initially this should be a determination of the basement ventilation rates and if high values of the volumetric source terms are validated then attempts should be made to identify the main sources of the radioactivity by taking selected soil, building materials, and utility samples.

Distribution Analyses for Other Contaminants

Introduction

Distribution analyses enables the investigator to infer from the data such basic information as:

1) Is the sample drawn from one general population (class) or are there more than 1 set of mechanisms (more than 1 population) from which the results were sampled.
2) Are there anomalies or outliers which lie outside the normal variance of the data and hence indicate either experimental errors or characteristics unique about the particular samples.
3) What type of distribution best describes the population. (For rate dependent variables such as radioactivity and chemical production, it is expected that the samples would demonstrate a lognormal distribution.)
4) For lognormal distribution, the geometric mean (median) is a good measure of the typical member of the population, i.e., for the class of houses investigated in this study the typical house would have the contaminant at the value given by the median. For this study, the value of the mean is a good estimator of the exposure of the individual who might live in a house of the type evaluated in the study.
5) The distribution analyses allows the examiner to predict the fraction of houses that would have contaminants above guideline or standard value. Conversely, the investigator can determine the level of contaminant in the majority (typically 90%) of houses which would not be exceeded.

Method

The method was the same as that employed for the radon analysis. For complete details the reader is referred to the references (King, 1971 and Aitcheson, 1957). Calculation of the distribution parameters was performed with a simple computer program written in Basic.

Results

Formaldehyde

Figure 4.4 demonstrates that the indoor average concentration of formaldehyde can be described by a single lognormal distribution. House 33 appears to be an outlier and the reason for the anomaly should be investigated. Outliers, however, do not impact on the overall distribution of the formaldehyde concentration.

Carbon Dioxide

As shown in Figure 4.5, two lognormal distributions are required to describe the carbon dioxide house average concentrations. House numbers 33, 41, 31, 45, 47, 32 and 36 belong to the distribution which predicts higher concentrations (median 740 ppm) while house numbers 37, 43, 48, 38, 50, 40 and 46 belong to the lower valued distribution (median 550). House numbers 34 and 44 may belong to either distribution. A plot (Figure 4.6) of the average carbon dioxide concentration in the house does not reveal any particular trend. Figure 4.7, the lognormal distribution of the carbon dioxide source term, the product of concentration multiplied by measured air exchange rate, does demonstrate that the sources all arise from the same general set of mechanisms. Owing to the non-specific and multi-variable sources of carbon dioxide in a house, this result is not surprising. The distribution analyses of the carbon dioxide concentration in different areas in the houses (Bedroom, Figure 4.8a, Main Floor, Figure 4.8b, Basement, Figure4.8c) all shown that the carbon dioxide levels for these areas can be described by single lognormal distributions. However, the bedrooms of house numbers 33 and 42 are outliers and the reasons for these peculiar results should be determined.

FIGURE 4.4 Distribution of Formaldehyde Data

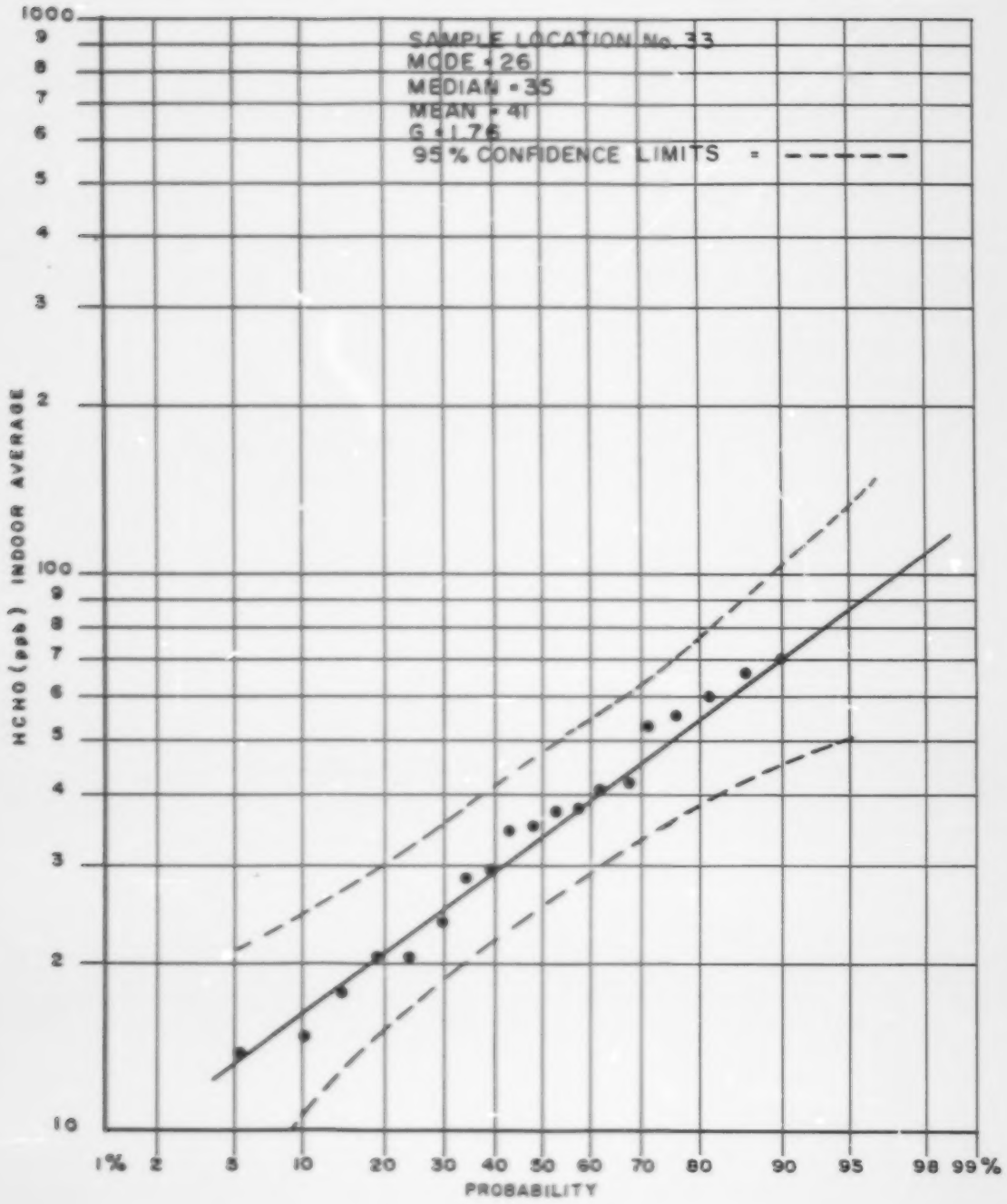


FIGURE 4.5 Distribution of CO_2 Data House Average

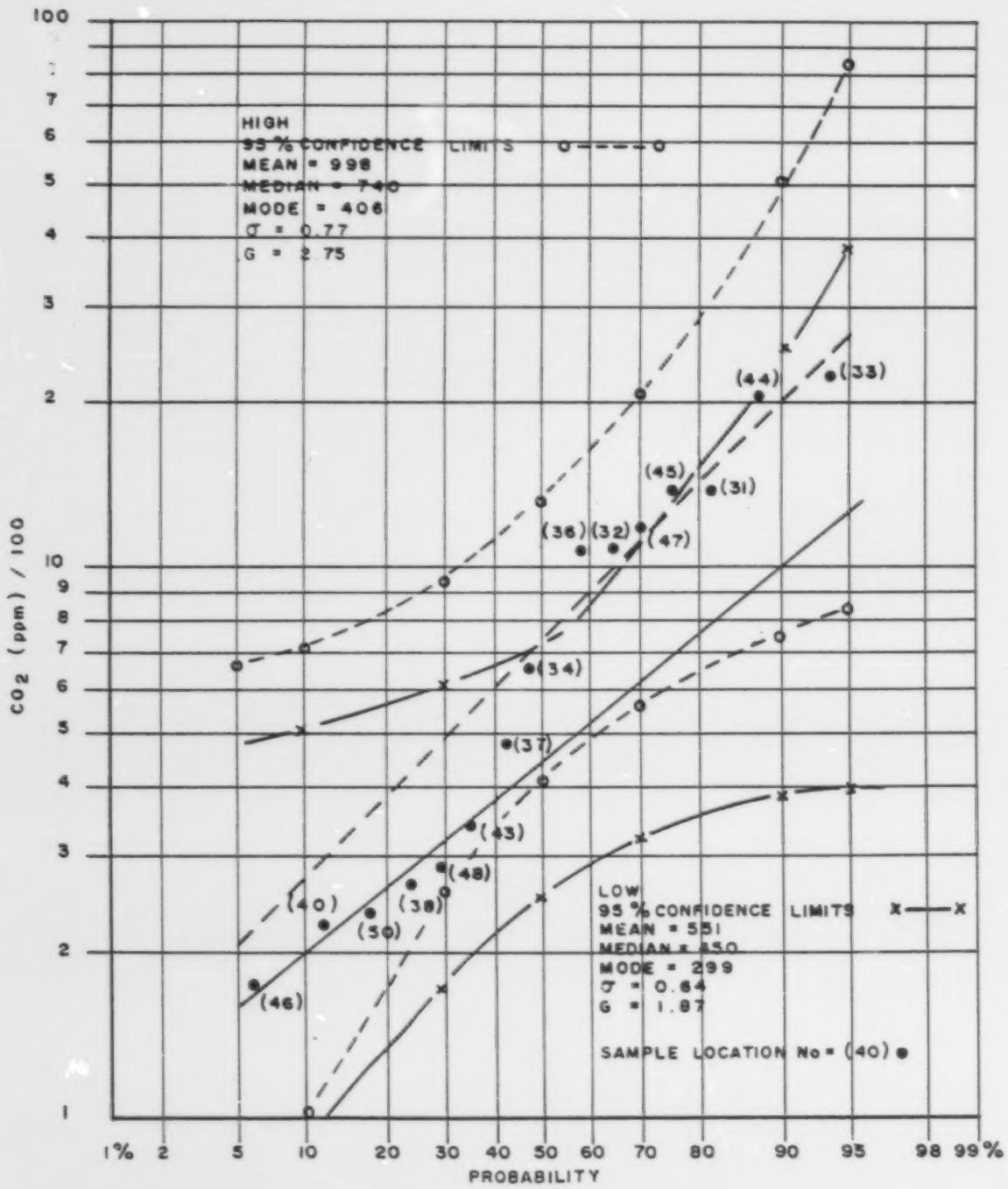


FIGURE 4.6 CO_2 Concentrations vs Air Change Rate

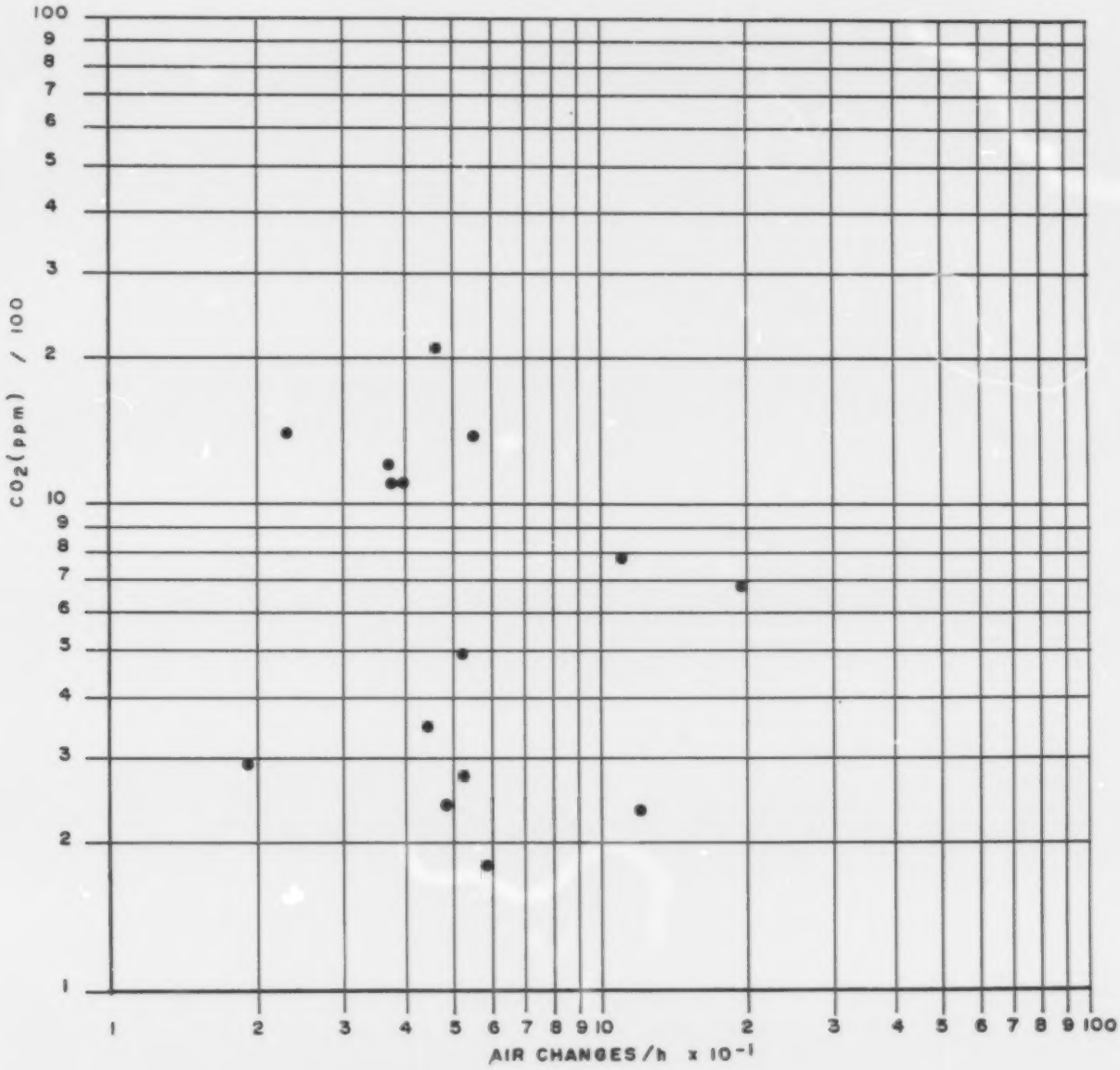


FIGURE 4.7 CO_2 Source Terms (ppm/h)

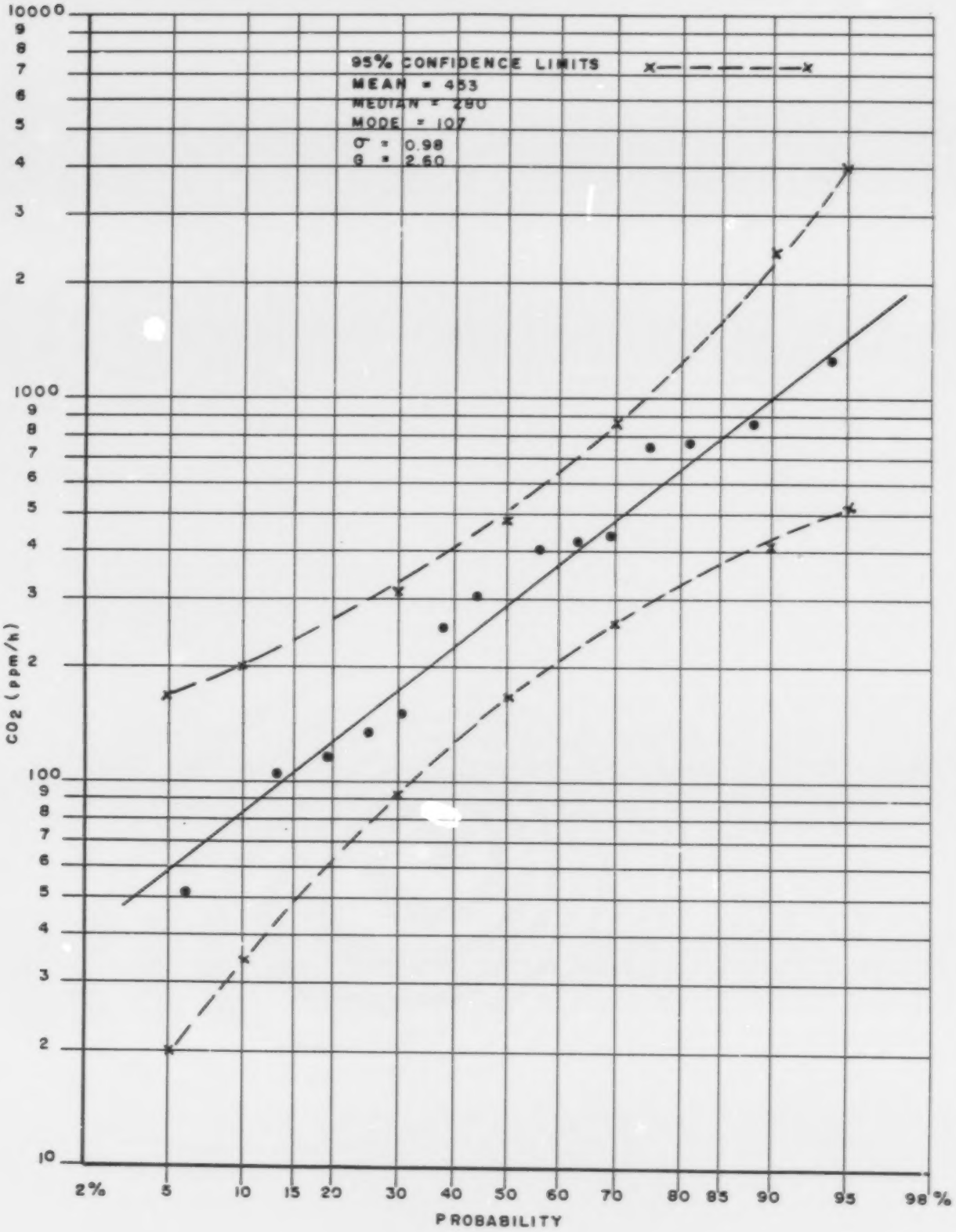


FIGURE 4.8a Distribution of CO_2 Data Bedroom

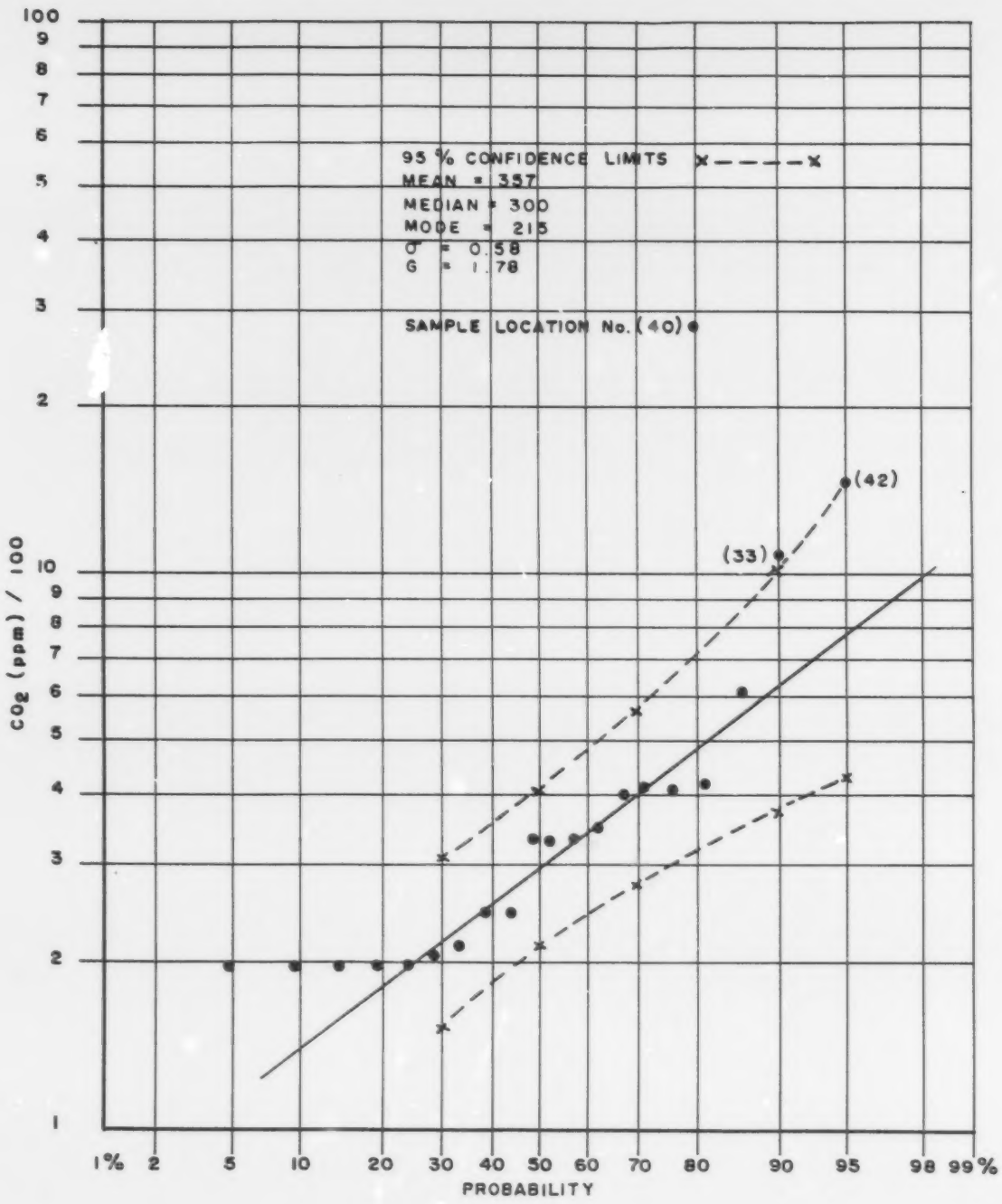


FIGURE 4.8b Distribution of CO_2 Data Mainfloor

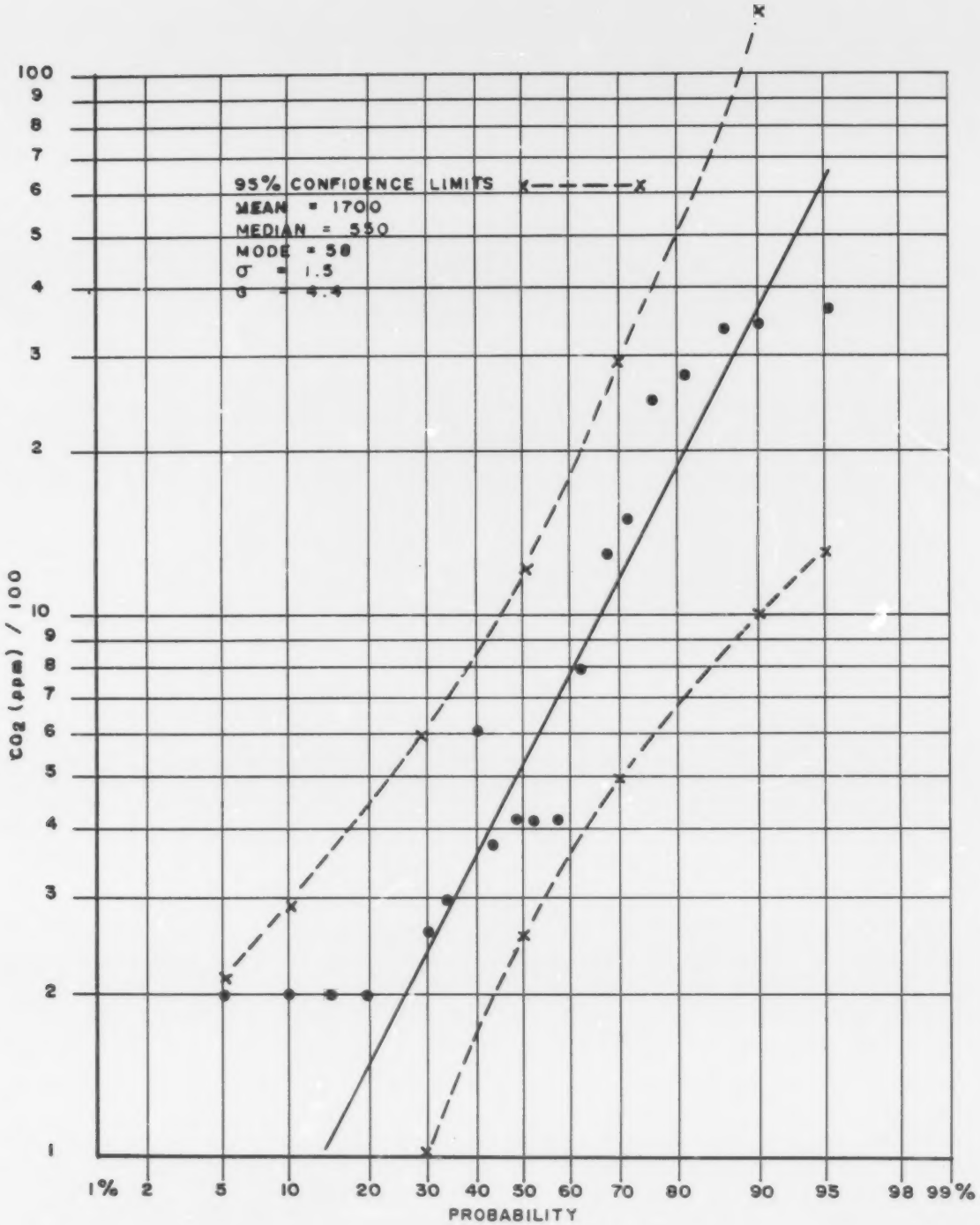
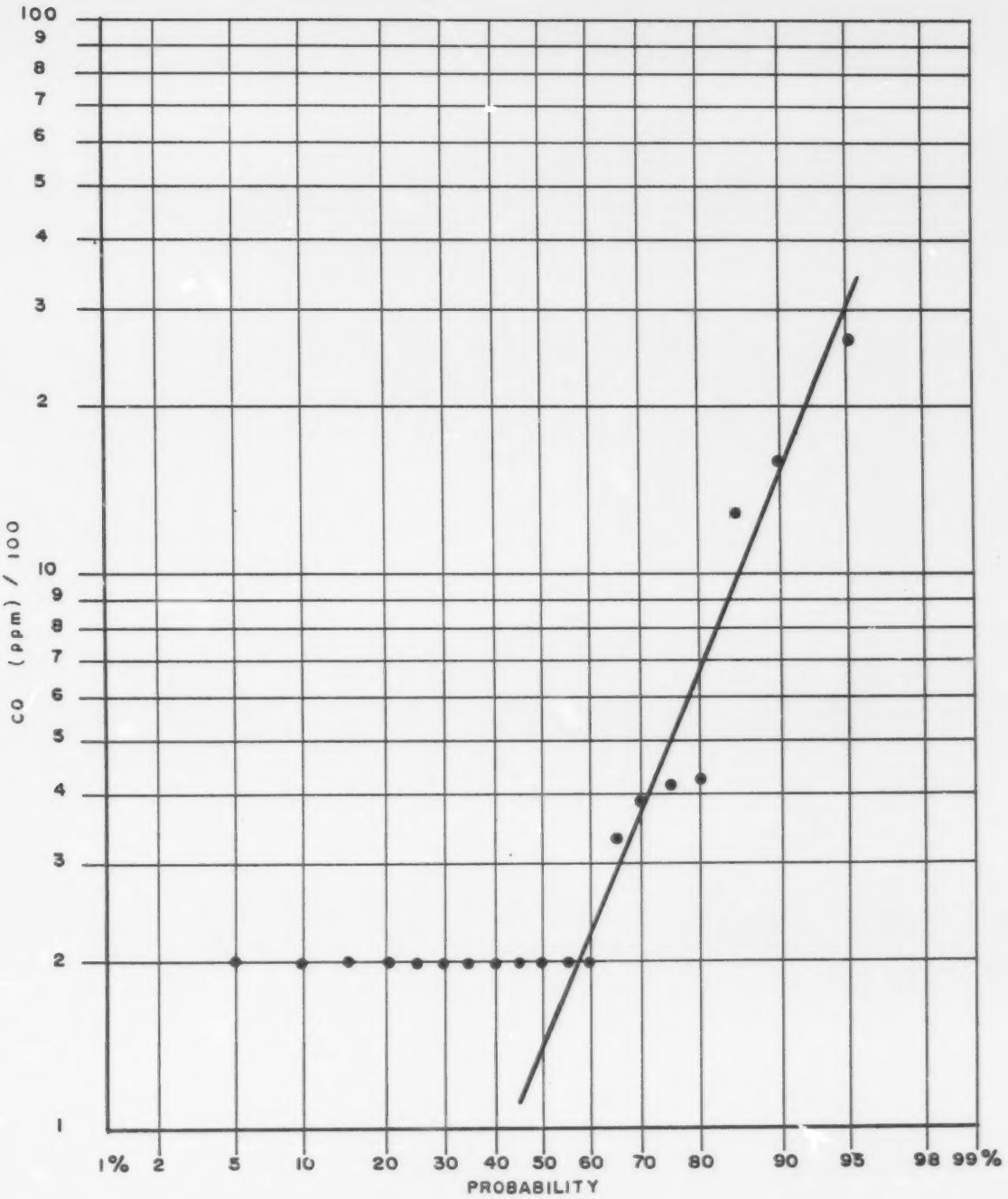


FIGURE 4.8c Distribution of CO_2 Data Basement



Carbon Monoxide

There was insufficient significant data to allow an analysis.

Nitrogen Dioxide

The distributions of nitrogen dioxide in the three areas of the houses were very similar, Figure 4.9. Three outliers were identified and should be investigated: the main floor and bedroom of house number 44 and the basement of house number 43.

Nitric Oxide

The lognormal distributions for this contaminant are shown in Figure 4.10. The distributions for the bedrooms and main floors are quite similar while that for the basement predicts lower concentrations. The basement of house number 47 was identified as an outlier and the main floor of house number 44 is tending towards being an anomaly.

Summary

An overview of the chemical contaminants is given in Table 4.11. All the median values are below the standard derived for this study, and with the exception of the carbon dioxide concentrations in the main floors and basements so are the means. However, if this population of houses is representative of houses given the special sealant treatment then the percentage of houses where contaminant levels will exceed the derived standards are given in Table 4.11.

Summary of Exceedances

The preceding information contained house by house discussions of the locations and probable causes of exceedances of the action level. While such a discussion sheds some light on the potential sources of poor indoor air quality it does not provide a clear picture of the relationships between sources and air quality in particular houses. Such a simplified picture is provided by Table 4.12 which summarizes the number of exceedances recorded for each contaminant by house.

FIGURE 4.9 Distribution of NO_2 Data

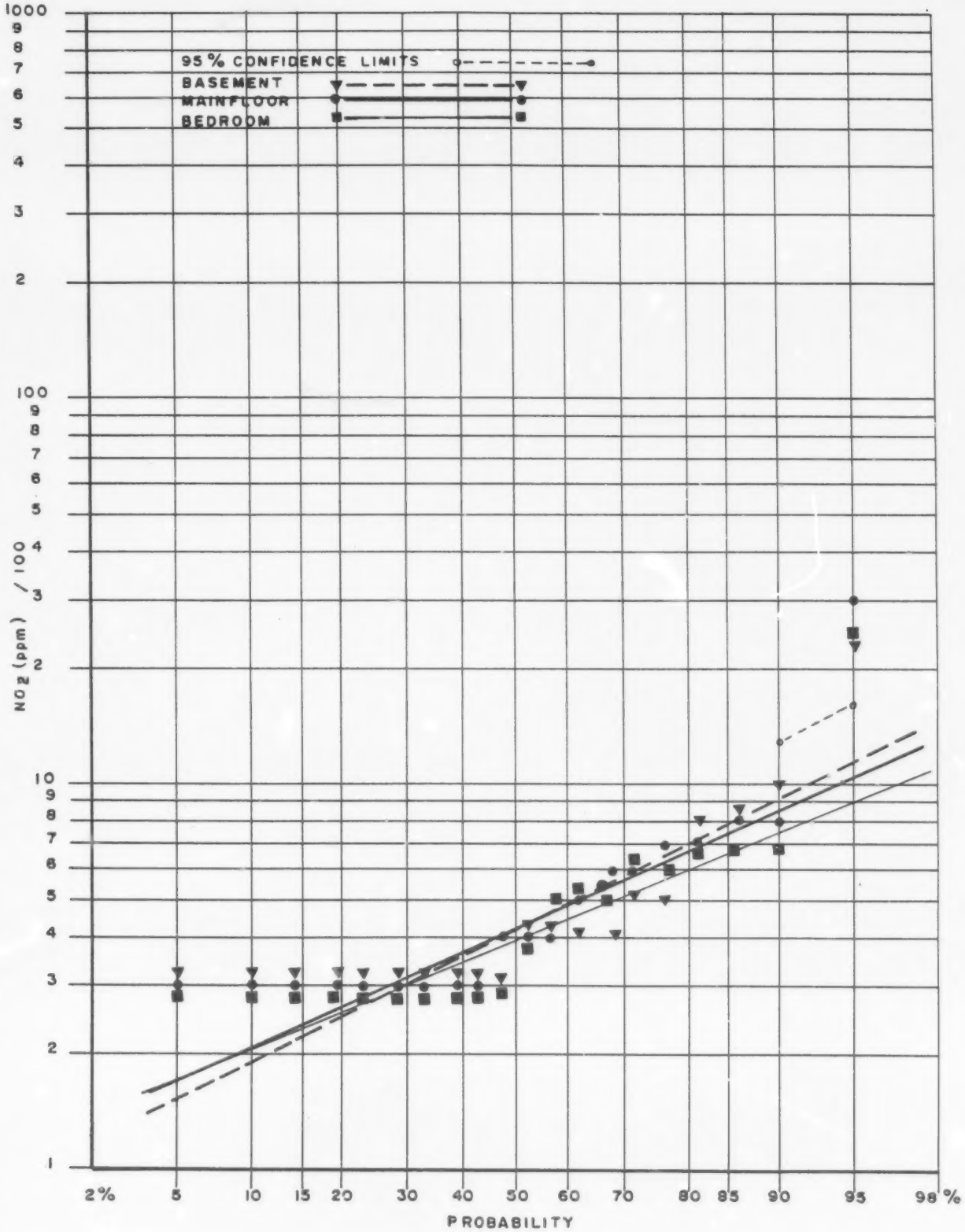


FIGURE 4.10 Distribution of NO Data

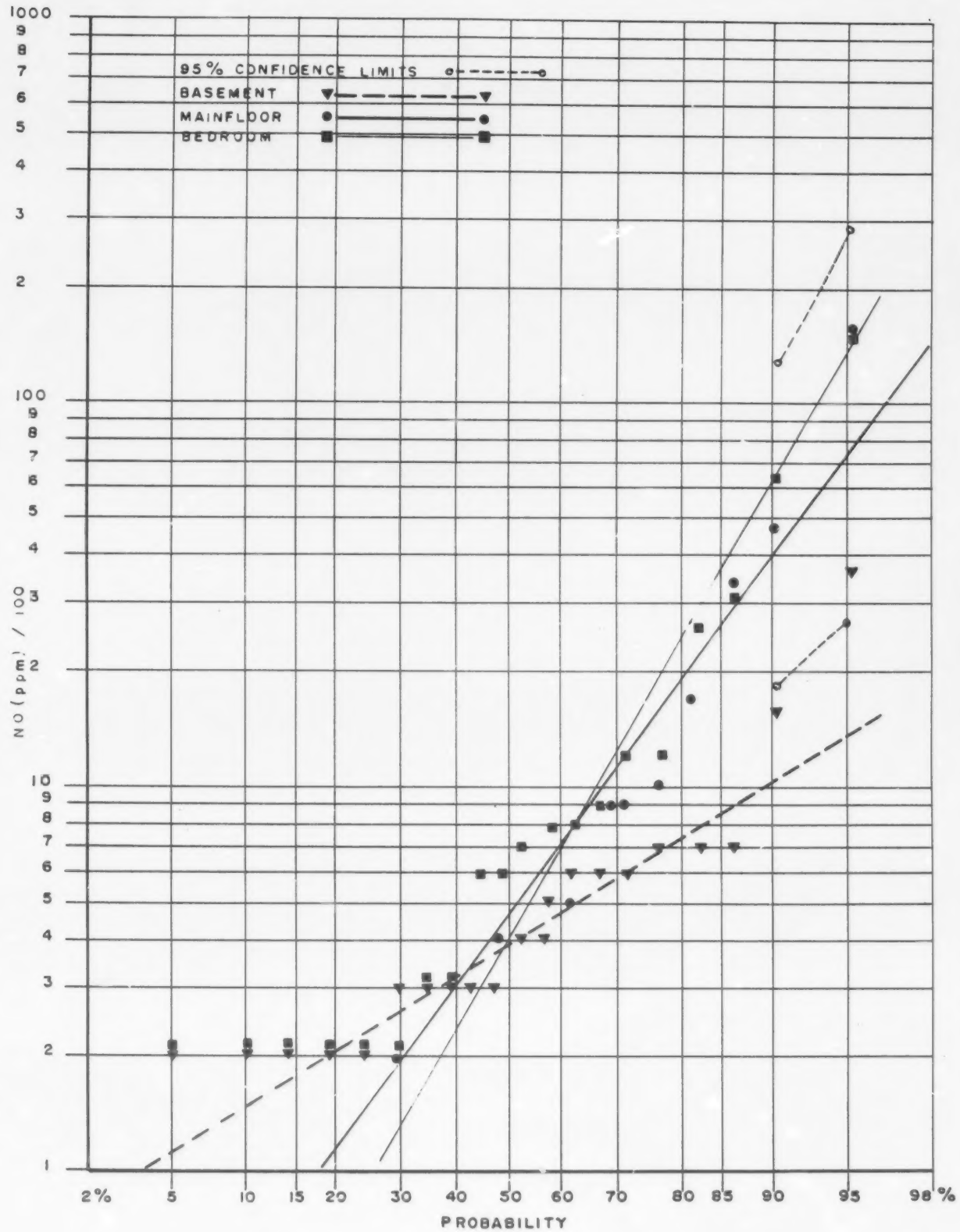


TABLE 4-11: DISTRIBUTION ANALYSIS OF CHEMICAL CONTAMINANTS

Chemical	Action Level	Median	Mean	90 Percentile	Percentage Greater than Action Level
Formaldehyde	50 ppb	35	41	70	25
Carbon Dioxide	600 ppm				
Bedroom		300	355	620	12
Main Floor		550	1700	3700	46
Basement		200	680	1500	21
Nitric Oxide	0.5 ppm				
Bedroom		4.4	26	65	13
Main Floor		4.8	19	40	8
Basement		3.9	5.1	10	1
Nitrogen Dioxide	0.15 ppm				
Bedroom		3.9	4.9	6.4	1
Main Floor		4.2	5.0	8.4	1
Basement		4.2	5.3	9.0	1
Radon	5 pCi/L	1.9	3.0	6.7	17

TABLE 4.12: NUMBER OF EXCEEDANCES OF SELECTED ACTION LEVELS FOR MEASURED VALUES OF INDOOR AIR QUALITY (Action Level in ppm)

House Number	Contaminant CO (2.5)	CO_2 (600)	NO (0.5)	NO_2 (0.15)	HCHO (0.05)	Rn (5 pCi/L)	Total
31	-	1*	-	-	-	-	1
32	-	2	-	-	1	-	3
33	-	2*	-	-	2	-	4
34	-	1	-	-	-	-	1
35	-	-	-	-	-	-	-
36	-	1	-	-	-	-	1
37	-	2	-	-	2	1	5
38	-	-	-	-	2	-	2
39	-	-	-	-	-	1	1
40	-	-	-	-	-	1	1
41	-	-	-	-	-	-	-
42	-	1	-	-	-	-	1
43	1	-	-	1	-	-	2
44	1	1*	2	2	2	-	8
45	-	2*	-	-	2	-	4
46	-	-	-	-	-	-	-
47	-	1*	1	-	-	-	2
48	-	-	-	-	-	-	-
49	-	-	-	-	-	-	-
50	-	-	-	-	-	-	-
Totals	2	14	3	3	11	3	36

* Indicates exceed 2500 ppm ASHRAE Criteria

Table 4.12 provides, at a glance, the results of this sampling study. It shows that a total of 36 exceedances were recorded on 300 readings. This is 12% of the total readings. On a percentage basis it can be noted that:

- 3% of the carbon monoxide readings exceeded 2.5 ppm,
- 23% of the carbon dioxide readings exceeded 600 ppm,
- 5% of the nitric oxide readings exceeded 0.5 ppm,
- 5% of the nitrogen dioxide readings exceeded 0.15 ppm,
- 27% of the formaldehyde readings exceeded 0.05 ppm, and
- 15% of the radon readings exceeded 5 pCi/L.

The number of exceedances for radon indicates that more screening work for radon in the subject homes should be undertaken.

The formaldehyde samples, while recording the highest percentage of exceedances, are part of a small sample group. Only six homes showed potential formaldehyde problems. The majority of the homes with potential formaldehyde problems have a generalized problem rather than a problem at one specific location. A comparison between the relative humidity data presented in Table 4.13 and formaldehyde levels in the homes was made on the basis of a calculated correlation coefficient. This showed that there was a strong correlation, at the one percent level, between moisture in the area and the formaldehyde value in the area. A five percent significant correlation was recorded between overall house moisture and overall house average formaldehyde level. A very complex emission/capture relationship is known to exist for formaldehyde. Carpet has been shown to absorb formaldehyde. The properties of this particular gas are such that it will tend to have an elevated off gassing rate under high humidity conditions so the correlation is not surprising. Given formaldehyde's role as a known sensitizer (Immuniglobin E), it is deemed appropriate to undertake a more thorough examination of the sources and levels of formaldehyde in the six homes where exceedances were recorded.

While only two homes were recorded to have carbon monoxide levels exceeding the selected action levels (Houses 43 and 44), an examination of the heating system and ventilation in these homes should be undertaken. The levels have not yet reached the critical level but they may be indicative of the particular problems in these homes.

Particularly worrisome is the elevated CO level recorded in the basement of House 43. This may be an indication of problems with the furnace ventilating system in that house. As the action for combustion testing was based on factors other than recorded pollutant levels in these houses, it may be appropriate to undertake some combustion tests in House 43.

The situation with nitrogen dioxide is identical to that of carbon monoxide. Two houses, the same two, record exceedances for this contaminant. Combustion testing in house 43 may shed some light on why the levels in that house appear to be higher than the norm.

While the percentage of exceedances of NO would appear to be higher than for NO_2 or CO the situation only occurs in two houses. Nitric oxide is generally thought to have a lower toxicity to humans than nitrogen dioxide and while it is probably worth investigating the potential sources of NO in house 47, no further work is anticipated.

The final contaminant in the list is carbon dioxide. Twenty seven percent of the carbon dioxide readings were in excess of the action level set for this study. These occurred in half the houses in the study. Being a product of the human metabolism, high levels of this substance are not considered to be particularly detrimental to human health. Only five levels in the study were recorded above the 2500 ppm ASHRAE standard for indoor ventilation. The presence of this contaminant would appear to be related to the total number of occupants in any particular home. At this time no further work is specifically recommended for CO_2 levels. If other work is undertaken in these homes the CO_2 levels could be investigated.

In the above summary discussion the author has avoided dealing with House 44. It is his opinion that steps should be taken to rectify indoor air quality problems in House 44.

4.3.4 Discussion of Other Test Results

Three other measurements were made during this program. These are:

- relative humidity inside the house,
- air exchange rates in the house, and
- combustion testing.

The results of these three tests will be discussed in this section of the chapter. Where possible these results will be related to prior testing done in the homes and results discussed in the previous sections of this chapter.

Relative Humidity Data

The relative humidity as measured in the houses are shown in Table 4.13. As a means of setting some action to ascertain the appropriateness of these levels of indoor humidity the instruction manual for a Wait Skuttle humidifier was consulted. The recommended levels of indoor relative humidity is a function of outdoor humidity as presented in Table 4.14.

A review of the data in Table 4.13 shows that higher relative humidities are recorded in some basements. This is particularly true in those cases where the basements tend to be relatively cooler than the rest of the house. This is not surprising since the absolute amount of moisture in the air probably does not vary that much between areas in the house.

A comparison of the data in Table 4.13 with that in 4.14 shows that eight houses have average relative humidities in excess of 10% greater than the recommended maximum given for the temperature outdoors on the day of testing. These levels could lead to moisture problems in the houses. Moisture is a problem in House 37 where the presence of mold and fungus was noted on the interior walls. House 37 recorded the highest average relative humidity with values ranging from 57 to 67%. House 44 recorded high relative humidities, and an average value 20% above the suggested level for the outdoor temperature on the day the house was tested. The relative humidity in House 44 however is still significantly below the levels achieved in House 37.

Two houses on the list, 40 and 48 have relative humidities significantly below the recommended levels. The balance of the houses fall into an acceptable range.

A statistical analysis of the percent relative humidity in the homes was undertaken by comparing that value to both infiltration rates and water usage. No significant statistical correlation resulted from either comparison. A supplemental fresh air inlet

Table 4.13: INDOOR TEMPERATURE AND RELATIVE HUMIDITY DATA

House #	Room	Wet Bulb Temperature (°C)	Dry Bulb Temperature (°C)	Relative Humidity (%)	Average Percent Relative Humidity
31	1st Floor Bedroom	12.5	19.5	41	
	Living Room	13.0	20.2	44	
	Basement	11.3	17.5	49	45
32	2nd Floor Bedroom	10.5	20.0	57	
	Living Room	13.0	19.0	52	
	Rec Room	11.0	16.0	36	35
33	1st Floor Bedroom	12.0	18.0	51	
	Living Room	13.3	20.0	48	
	Rec Room	8.5	15.2	35	45
34	2nd Floor Hallway	9.5	17.5	36	
	1st Floor Den	9.0	16.5	37	
	Basement	9.0	12.0	68	47
35	1st Floor Bedroom	14.0	22.5	40	
	Living Room	13.0	20.5	43	
	Basement	10.5	18.0	40	41
36	2nd Floor Hallway	13.0	22.0	36	
	Living Room	13.0	21.5	38	
	Basement	10.0	18.0	36	37
37	2nd Floor Bedroom	15.0	19.0	67	
	Living Room	14.0	19.5	57	
	Basement	14.0	19.5	57	60
38	2nd Floor Bedroom	15.0	20.5	57[1]	
	Living Room	12.0	18.5	48	
	Rec Room	12.5	20.0	43	49
39	1st Floor Bedroom	14.0	20.5	50	
	Living Room	14.5	21.5	48	
	Basement	13.0	19.5	49	49
40	2nd Floor Bedroom	9.5	19.0	28	
	Den	9.0	18.5	28	
	Basement	8.0	13.5	47	34
41	2nd Floor Bedroom	12.5	19.5	45	
	Living Room	13.5	20.5	47	
	Rec Room	11.0	19.0	38	43
42	2nd Floor Hallway	13.0	20.5	43	
	T.V. Rm. Living Rm.	12.5	19.5	46	
	Basement	9.5	15.0	49	46
43	2nd Floor Bedroom	13.0	21.0	41	
	Living Room	14.5	22.5	43	
	Rec Room	12.5	20.0	43	42
44	2nd Floor Bedroom	12.3	16.5	63	
	Kitchen	14.0	20.0	53	
	Basement	9.0	14.0	52	56
45	2nd Floor Bedroom	13.5	22.5	37	
	Kitchen	13.5	22.0	39	
	Rec Room	13.0	18.5	55	44
46	1st Floor Bedroom	11.5	16.0	60	
	Living Room	12.0	18.5	48	
	Rec Room[2]	10.5	17.5	43	50
47	2nd Floor Bedroom	11.5	18.5	44	
	Den	12.0	20.0	40	
	Basement	9.0	16.5	37	40
48	2nd Floor Bedroom	9.0	18.5	28	
	Living Room	8.0	16.5	30	
	Basement	7.0	15.2	21	26
49	2nd Floor Bedroom	11.0	19.5	38	
	Living Room	12.0	20.0	40	
	Basement	8.5	16.5	34	37
50	2nd Floor Bedroom	13.0	21.0	41	
	Kitchen	11.5	20.0	36	
	Basement	5.0	12.5	30	36

1. Portable Humidifier operating 2. Wood Stove operating

TABLE 4.14: RECOMMENDED INDOOR RELATIVE HUMIDITY AS A FUNCTION OF OUTDOOR TEMPERATURE*

Outdoor Temperature °C	Relative Humidity %
-29	15
-23	20
-18	25
-12	30
- 6	35
- 6	40

Recommended normal level for humans 50 - 55% RH

* from Wait Skuttle Humidifier Instruction Manual

has been placed in homes 31, 42, and 49. With these units in place the relative humidity levels in those three houses are not excessive. This simple modification would appear to provide one means of controlling humidity in the homes.

Infiltration Rates

As has been noted before, infiltration rates, expressed in air changes per hour, are presented in Table 4.4. This data has been used to undertake comparisons between the various airborne contaminants in the houses and the rate at which air is exchanged in the house. No significant correlation coefficient between any of the contaminants and the air infiltration rates measured in these homes was found. The testing procedure does not provide an indication of individual room air change rates. Thus, the lack of a correlation between general air change rates and individual concentrations is not surprising.

It will be noted, from a review of Table 4.4, that the air exchange rates measured using the SF_6 testing technique range from a low of 0.11 ACH to a high of 1.92 ACH discounting the questionable result from House 43. Some scatter is present in the calculated air exchange rates from the initial test and the second test.

Having found no significant correlation coefficient between the air infiltration rates in any of the indoor contaminants measured in this study a check was run between the measurement results of this study and that of the previous sealing study.

The tracer gas method for assessing air change rates in houses is relatively simple and convenient to use. No great disturbances are caused to the residents of the house and no particularly difficult preparation is required. The blower door testing procedure utilized by the contractors sealing the Cambridge houses, works on a different principle. During this testing program a negative pressure is applied to the house and a calculated effective open area is derived. After sealing the house the blower door test can be run again to ascertain the decrease in effective open area. By subjecting the house to higher negative pressures than may occur during most climatic conditions, or for most occupant uses of the building, a value free from small interferences is obtained. In Appendix 2, under the subject of Radon, the potential variations in air exchange rates in houses are discussed, particularly with respect to the work of Kusuda (1980). Minor fluctuations in air exchange rates occur continuously in the house as different operations occur and as

the wind picks up or decreases outside. In an attempt to provide a correlation between the blower door tests and the tracer gas tests, the conventional correlation coefficient, r, was calculated for the blower door testing results and the air exchange rates.

The value of the correlation coefficient for the final set of blower door tests with the tracer gas tests was 0.33, the value for the second last blower door test in each house and the tracer gas tests was 0.39. The second last test data was checked because, in many cases, it appeared to provide a lower effective open area than noted in the last test. These correlations coefficients are not significant when compared to standard statistical tables with 18 degrees of freedom and two variables. At the five percent level, the correlation coefficient is significant at 0.444 for 18 degrees of freedom and two variables.

The lack of correlation is not really surprising considering that the houses were tested with the blower door at the completion of the sealing operations. The elapsed time between that test and the tracer gas tests conducted for this study would be sufficient to allow some changes to the outer envelope of the house. Total sealing of all potential areas of fresh air intake to the houses was not conducted during the tracer gas tests. Items such as fireplaces and furnace exhaust stacks are generally blocked off during the blower door tests. The variations in the test protocols would be sufficient to change the results of the tests.

Combustion Testing Results

Table 4.15 shows the results of the combustion tests. The table lists the percent CO_2 concentrations measured in both the burner section of the furnace and after the draft hood. Sequential results are presented for each house as additional exhaust fans were turned on in the house. The data also shows the stack pressures in inches of water. As additional devices were turned on in each home, changes in such pressure and the various carbon dioxide concentrations were recorded.

Both oil and gas furnaces were checked for combustion characteristics. The oil furnaces were present in houses 31, 35 and 48. The balance of the furnaces were gas. Only one average measurement was made on the burner carbon dioxide concentration in the oil furnaces. It should be noted that oil furnace CO_2 concentrations are used as a measure

Table 4.15: COMBUSTION TESTS AVERAGE RESULTS

	Percent CO_2 Concentration					Stack Suction Pressure in inches (WC)
	Furnace Burner			Exhaust Duct		
House #31**						
Furnace		8.0			5.0	0.040
Furnace, KEF		7.5			6.5	0.035
Furnace, KEF,BEF		7.5			6.5	0.035
Furnace, KEF,BEF,FP		7.5			6.5	0.030
House #32						
Furnace	6.0	5.5	7.0		3.0	0.040
Furnace,WH	6.0	6.5	6.5		3.5	0.035
Furnace, WH,KEF	6.0	5.0	6.0		3.5	0.035
House #35						
Furnace		11.5			7.0	0.035
Furnace, D		11.5			7.0	0.035
House #42						
Furnace	6.5		6.5		2.8	0.020
Furnace, FJ	7.0		7.0		3.5	0.015
Furnace, FJ, D	7.0		6.5		3.8	0.015
Furnace, FJ. D, WH	7.0		6.5		3.0	0.015
House #44						
Furnace	6.0		6.0		2.3	0
Furnace, D	6.0		6.0		1.5	0
House #47						
Furnace	6.5		7.0		3.0	0.035
Furnace, BEF	6.0		6.0		2.5	0.025
Furnace, BEF, KEF	6.0		6.0		2.5	0.025
Furnace, BEF, KEF, FP	6.0		6.0		2.5	0.025
Furnace, BEF, KEF, FP,D	6.0		6.0		2.0	0.015-0.045[1]
House #48						
Furnace	8.0		6.5		0.055	
Furnace, D	8.0		6.3		0.055	
Furnace, D, FP	7.5		6.5		0.045-0.050	
House #49						
Furnace	5.5		6.0		3.0	0.030
Furnace, BEF	5.5		6.5		3.0	0.025
Furnace, BEF, KEF	5.5		6.0		3.0	0.025
Furnace, BEF, KEF, WH	5.5		6.0		3.0	0.025
House #50						
Furnace	6.0	7.5	7.0	7.0	5.0	0.015
Furnace, D	7.0	7.5	8.0	7.0	5.0	0.020
Furnace, D, HW	7.0	7.0	7.5	6.5	4.5	0.025

KEF Kitchen Exhaust Fan
BEF Bathroom Exhaust Fan
WH Water Heater
FP Fireplace
D Dryer
FJ Furnijet

** all tests run with furnace on and each extra exhaust device added in sequence

1 very erratic, house filled with smoke

of performance characteristics of the burner and the fact that house 35 shows a significantly higher carbon dioxide concentration in the furnace indicates that that furnace is probably in better tune than the furnaces in houses 48 and 31.

Gas furnaces will tend to maintain a carbon dioxide concentration much closer to the optimum 6 to 7 percent CO_2. This value is noted in most of the tests with slight variations in carbon dioxide concentration in gas burners. The gas furnaces generally have more than one combustion chamber being of the, now common, clam shell type arrangement. House 44 with its gravity gas furnace is a slight departure from this practice but additional measurements were made in this furnace to provide two sets of measurement for this study. In both oil fired furnaces and gas fired furnaces it is anticipated that the exhaust duct carbon dioxide concentration will be diluted by air entering the stack through the barometric damper or draft hood. This fact is noted in all the homes where substantial reductions are recorded in carbon dioxide concentrations in the exhaust stack. With the gas furnaces the rate of dilution would appear to be significantly higher than with oil furnaces. The gas furnace exhaust stack concentrations are half the average burner concentrations.

No substantial change occurs in carbon dioxide concentrations in any of the furnaces regardless of the number of exhaust devices operating in the house. Sufficient scatter exists in the data to indicate that the carbon dioxide concentration is not strongly affected by negative pressures on the house envelope. It should be noted that the negative pressures expressed in this report are purely those superimposed by operating various exhaust devices in the house. Particular circumstances, which give rise to increases in negative pressure on the house not accounted for during this study, may produce substantial changes in carbon dioxide concentrations. Stack draft measurements, in inches of water column, do vary somewhat, however, with changes in the number of exhaust devices in the home. Generally speaking there is a marginal decrease in draft negative pressure as the number of exhaust devices rises although the measurement procedure is insensitive given the variations caused by winds.

Only in the case of house 47 were substantial variations noted when the last exhaust device was turned on. In this particular house a very erratic behaviour on the stack draft gauge occurred when the dryer was turned on and all the other devices were operating. The effect of turning the dryer on was to cause a reverse flow in the fireplace chimney

and the house filled with smoke. This indicates an insufficiency of fresh air make up in this house. The air infiltration rate in this particular house was measured at 0.37 ACH on the second testing.

The results of the contaminant testing in the houses showed a couple of houses where concerns were raised as to high CO and nitrogen dioxide levels in the basement. These houses were not tested as part of the combustion testing program of this study and transient reverse draft situations, such as spillages from the gas furnace draft hoods, may be occurring on furnace start up. The situation could be exaggerated by high negative pressures on the house but the study team has no data to verify or refute this supposition. Generally speaking, no significant problems were turned up during the combustion testing phase of this study.

5.0 CONCLUSIONS AND RECOMMENDATIONS

Table 4.12 presented the recorded exceedances of air pollutant concentrations over a selected action level. The sampling techniques were limited but they did show some potential problems with 14 of the 20 Cambridge houses. The test program raises several questions:

- o do the measurements really reflect the long term situation in the houses?
- o were the techniques specific enough to rely on the results for remedial decisions?
- o were the measured levels the result of air sealing the houses? and
- o are the action levels appropriate?

The first two questions relate to the need for repetitive sampling to confirm levels and the need for quality assurance checks on the data. The third question cannot be answered without pre-sealing testing. The fourth question will be the subject of considerable scientific work over the next 3-5 years. The levels selected can only be judged a starting point and while one might argue that some are too low, in all likelihood most would not be considered to be too high by most parties. The levels thus tend to err on the side of safety.

If one could answer the first two questions in the affirmative, the next step must surely be to select appropriate remedial measures to reduce levels to acceptable values. If the exceedances are random the problem of selecting remedial measures is more difficult since one cannot pinpont the source. Based upon the data gathered to date, a program of follow-up study and remedial measures has been developed and will be the subject of further work. Before dealing with each house in turn some general approaches should be discussed.

Carbon dioxide, while not considered critical, may, in high concentrations, cause difficulties. Complaints of "poor air" in office buildings have been correlated to CO_2 levels above the action level selected. In homes, high levels are likely the result of poor circulation. Circulation patterns in the homes should be examined. Where these are not found to be adequate remedial measures should be instituted.

The radon results reported in this study are the product of a single measurement in each home. Some retesting, as outlined in the previous chpater, is necessary to both confirm the level and identify the potential source of the gas. After identification remedial measures and additional testing can be undertaken.

We would only recommend immediate remedial measures for House 44. The presence of a gas range and a retired smoker with a particular lifestyle are assumed to contribute to the high levels of all contaminants in this house. The addition of a range hood in the kitchen and a bathroom exhaust fan upstairs would remove some of the pollutants.

One might well ask - what can be derived from this study? With the lack of IAQ data for the houses prior to sealing, all conclusions and possible explanations presented are at best suppositions.

It was obvious that localized indoor air quality in many of the homes is a function of sources and circulation patterns. Carbon dioxide concentrations are an appropriate indicator of the efficient of ventilation in a house. Higher levels of CO_2 will indicate potential locations with high concentrations of other contaminants.

Sealing homes with gas ranges provides the greatest potential for generatirg poor indoor air quality particularly if the range is not vented. Similarly, given the off-gases from kerosene heaters sealing in houses where these are used should be carefully considered.

Before any sealing is undertaken, some consideration of the house, the occupants' lifestyle and the equipment in the house should be undertaken. Homeowners must be made aware of the potential for poor air quality, increased humidity levels and the other problems associated with reduced ventilation. They can then take steps to rectify any problems should the occur. In addition, a review of the presently installed ventilation will allow the sealing contractor to adjust the degree of sealing to accommodate individual circumstances.

Further study of the effects of sealing is necessary and in the interim a minimum air change rate should be set to encompass the equipment and uses in the residence.

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APPENDIX 1

APPENDIX 1

WEATHERIZE PROJECT

FINAL HOMEOWNERS LIST FOR THE CITY OF CAMBRIDGE

31 Galt, N1S 1Z3, 1 storey wood frame with oil heating, (1946-60)

32 Hespeler, N3C 2X6, 2 storey wood frame with gas heating, (After 1970).

33 Galt, N1S 2B3, 1 storey wood frame with electric heating, (1946-60).

34 Hespeler, N3C 1P6, 2 storey wood frame with gas heating, (Before 1920).

35 Hespeler, N3C 1C6, 1 storey wood frame with oil heating, (1946-60).

36 Galt, N1S 1R3, 2 storey wood frame with gas heating, (1946-60).

37 Preston, N3H 5G4, 2 storey wood frame with electric heating, (After 1970).

38 Preston, N3H 4X3, 2 storey wood frame with electric heating, (After 1970).

39 Galt, N1R 3Z1, 1 storey wood frame with oil heating, (1920-45).

40 Hespeler, N3C 1G6, 1 1/2 storey wood frame with oil heating, (Before 1920).

41 Galt, N1R 1M9, 1 1/2 storey wood frame with electric heating, (1961-70).

42 Galt, N1S 4H1, 2 storey wood frame with gas heating, (After 1920).

43 Galt, N1R 5M3, 1 1/2 storey wood frame with gas heating (After 1920).

44 Preston, N3H 3R3, 2 storey wood frame with gas heating, (1920-45).

45 Hespeler, N3C 2R8, 1 1/2 storey wood frame with gas heating, (1920-45).

46 Galt, N1R 2R8, 1 storey wood frame with electric heating, (1961-70).

47 Galt, N1R 5M4, 1 1/2 storey wood frame with gas heating, (1961-70).

48 Galt, N1S 1X8, 2 storey wood frame with oil heating, (1920-45).

49 Galt, N1S 4H1, 2 storey wood frame with gas heating, (After 1970).

50 Preston, N3H 3R3, 1 1/2 storey wood frame with gas heating, (1920-45).

House Number _____

HOMEOWNER QUESTIONNAIRE

Home Owner _____

Street _____ City/Town _____

Province _____ Postal Code _____ Tel. No. Bus: _____ Res: _____

Sampling Date/Time Tentative _____

Confirmed _____

Sampling Technician _____

1.0 DWELLING DESCRIPTION

1.1 Type of Dwelling:

Single Detached
Semi Detached
Row
Duplex
Apartment
Other _____

Number of storys excluding basement: _____ Age _____

1.2 Garage

Is there a garage?_____

Size? 1 car, 2 cars?_____

Attached to dwelling or separate?_____

Common door between garage and dwelling?_____

1.3 Basement

Is there a basement?

Full___ Crawl___ Dirt Floor____ Concrete Floor ___ Sump____

Finished: Floor___ Wall____ Ceiling ____ % of Total_____

Cracks Present: Floors ____ Walls_____

Comments _____

_____

1.4 Doors:

	Front	Side	Rear
Single Door Set	___	___	___
Double Door Set	___	___	___
Wood - Hollow Core	___	___	___
- Solid Core	___	___	___
Metal Clad - Insulated	___	___	___
Glazing - None	___	___	___
- Single	___	___	___
- Double	___	___	___
Storm Door - None	___	___	___
- Wood	___	___	___
- Aluminum	___	___	___
Weatherstripping	___	___	___

Sliding Doors - Yes No No. of sets _____

Type: Wood Vinyl Clad Wood Aluminum

Comments _____

_____

1.5 Dwelling Interior Analysis

Interior Wall Finish:

Type _____

_____

Condition _____

Detailing at Corners _____

Mouldings _____

Comments _____

_____

Windows:

Type _____

Condition _____

Tightness _____

Vent Holes Plugged? N.A. Yes No

Evidence of icicles hanging from sills? Yes No

Condition of sills/frame _____

Comments _____

_____

Ceiling:

Type _____

Condition _____

Comments _____

_____

Attic:

Type _____

Size _____

Attic Venting -

Power Eave - Continuous Ridge - Continuous Roof

- Individual - Individual

Condition/Comments _____

_____

Attic Hatch:

Location Insulated Weatherstripped

1.6 Fireplaces:

How many fireplaces does your home have? _____

Does fireplace have a fresh air supply? Yes No

Please check type(s) of enclosure(s):

Open Screen

Glass Door

Metal Door

Insulated Plug

How many fireplaces are equipped with dampers? _____

How many chimneys does the home have? _____

1.7 Present Insulation:

Type: Batts - Fibreglass _____

- Rockwool _____

Slab Insulation _____

- Styrofoam _____

- Other _____

Blown Insulation _____

- foam _____

- Cellulose _____

- Mineral Wool _____

Air/Vapour Barrier Type _____

Other Insulation _____

Insulation thickness (inches): Wall _____

Ceiling/Attic _____

Basement _____

Floor (over inheated area) _____

1.8 Recent Energy Retrofit Activities-After Weatherization

Areas Retrofitted: Attic/Ceiling New Windows

Above-grade Walls Added Storm Windows

Basement Walls New Doors

Floors Added Storm Doors

Caulking Weatherstripping

Date of Retrofitting _____

Other: _____

1.9 Miscellaneous

Approximate number of indoor plants? _____

Are drapes heavy material or lined? _____

Location _____

Fish tank or aquarium? Yes No

Size _____

Closed Open

Are air purifiers used in house _____

If so, where? _____

1.10 Dwelling Exterior Analysis

Chimney: Type _____ Number _____

Condition _____

_____

Roof: Buckling Waviness Ice Damming

Comments _____

_____

Soffit Condition: Peal Rot

Slope - In line with roof flat

Soffit Vents

Comments _____

_____

Exterior Siding: Type _____ Gen. Tightness _____

Caulking around doors and windows _____

_____

Paint Condition (blistering, peeling, etc.) _____

_____

Brick:

Brick Spalling		Yes	No Location
Efflorescence	Yes	No	Location
Weep Holes	Yes	No	

Comments _____

_____

Foundation:

Type _____

Average Projection _____

Does grade slope away from house? Yes No

Skirtboard, etc. Rot Water Marking

Under-skirt Edge _____

_____

Comments _____

_____

2.0 OCCUPANT INFORMATION

Number of Occupants _____

Ages _____

Total number who smoke _____

Number of occupants home during day _____

Number who smoke _____

3.0 HEATING: Type	Fuel Used	Percent Used
Steam/hot water	Oil	_____
Forced hot air	Gas	_____
Gravity hot air	Electricity	_____
Radiant	Coal	_____
Baseboard	Wood	_____
Fireplace/stove	Other	_____

Temperature Control:

Thermostat Location _____

Normal Daytime Setting _____

Normal Nighttime Setting _____

Use of thermostat setback:

Never Infrequent Frequent

Set Back Thermostat

4.0 HUMIDITY/VENTILATION:

Humidifers: None Furnace Plate Type Furnace Drum Type

Portable Console Type

Normal winter setting, %

Is a combustion air intake present on heating system? Yes No

Ventilation: Is dryer exhaust vented to exterior? Yes No

Exhaust Fans:

None _____

Kitchen__ Vented to exterior Flowrate (CFM)

Bathroom__ Vented to exterior Flowrate (CFM)

Attic ____

Other ____

Exhaust Fan Use

	Never	Infrequent	Frequent
Kitchen	___	_____	_____
Washroom	___	_____	_____
Other	___	_____	_____

When fireplace is not is use are dampers kept closed? Yes No

When lighting the fireplace do you often have difficulty initiating the draft?

Yes No

5.0 WATER USAGE:

Number of sinks in house _____

Number of showers in house _____

Number of baths in house _____

Approximate water used per month, m^3 _____

Type of fuel for hot water heater _____

Is there an automatic dishwasher used? _____

Laundry Activities:

Clothes Washing: Automatic Tub

Frequency of use per week _____

Clothes Drying: Inside Line

Automatic

Frequency of use per week _____

Cleaners used: Detergents

Bleach

Other _____

Are fabric softeners used in the washing cycle or in the dryer?

6.0 COOKING:

Type of range Electric _____

Gas _____

Other _____

Rank the methods of cooking by frequency of use: (0 - not used, 5 - most frequent)

Fry _____

Broil _____

Bake _____

Microwave _____

Other _____

7.0 ASSESSMENT OF HOME COMFORT LEVELS:

Please assess the comfort level within the main living area of your home (i.e., exclude basement and storage rooms) related to each of the following criteria during recent heating seasons.

	Good	Average	Poor
Humidity Level	____	____	____
Room Temperature	____	____	____
Floor Temperature	____	____	____
Heat Distribution	____	____	____
Odour ____	____	____	
Drafts - Doors	____	____	____
- Windows	____	____	____
- Floor Area	____	____	____
- Fireplace	____	____	____
- Electrical Outlets	____	____	____

For any criteria which has been marked "Poor" please comment:

_____

_____

_____

8.0 INDICATION OF PROBLEMS:

Problem:	Location/Comments
Ceiling	
Staining	_____
Mould	_____
Water in Fixtures	_____
Dust Marking	_____
Deterioration	_____
Collapse	_____
Cracking	_____
Peeling	_____
Walls	
Staining	_____
Mould:	_____
General	_____
Behind Drapes	_____
In Closets	_____
Dust Marking	_____
Deterioration	_____
Cracking	_____
Peeling	_____
Windows	
Inner Pane	_____
Frosting/Condensation	_____
Outer Pane	_____
Frosting/Condensation	_____
Frame Rotting	_____
Wall Deterioration	_____
Below	_____
Basement	
Mould	_____
Efflorescence	_____
Damp	_____
Water Running from	_____
behind insulation	_____
Bulging of	_____
insulation/finish	_____

APPENDIX 2
STANDARDS AND REPORTED LEVELS

A2 STANDARDS AND REPORTED LEVELS

A2.1 Standards for Measured Contaminants

While ambient air quality standards (AAQS) are defined for numerous substances, and standards exist for 1/2 hour concentrations of other substances in the province of Ontario, the only substances considered in this report are those that were measured in the Cambridge homes. The various standards that are available for examination include:

- the Canadian Ambient Air Quality Objectives as set by the federal government and regulated by the various provinces (EPS, 1976),
- the United States National Primary and Secondary Ambient Air Quality Standards (40 CFR Part 50),
- the Workplace Threshold Limit Values published by American Conference of Governmental Industrial Hygienists (ACGIH, 1983),
- the Standard for Ventilation Required for Minimum Acceptable Indoor Air Quality published by American Society of Heating Refrigerating and Air Conditioning Engineers (ASHRAE, 1980),
- the Canadian Standard for Formaldehyde in UFFI homes, (UFFI/ICC criteria), and,
- criteria for radon (AECB, 1977).

Carbon Monoxide

Carbon monoxide is a stable product of incomplete combustion. It is not readily perceived by humans as it is a colourless, odourless substance. It is commonly given off by gas fired appliances, smoking, and the major contributor, automobiles. Three major standards have been adopted for carbon monoxide levels. In Canada, the Ambient Air Quality Objectives provide standards for 1 hour exposures and 8 hour exposures under both the desirable and acceptable classification. These values refer to outdoor air quality concentrations and are as follows:

Carbon Monoxide

Canada (EPS, 1976)	8 hour desirable	0 - 6000 ug/m^3 (0 to 5.5 ppm)
	8 hour acceptable	6000 - 15000 ug/m^3 (5.5 to 14 ppm)
	1 hour desirable	0 - 15000 ug/m^3 (0 to 14 ppm)
	1 hour acceptable	15000 - 35000 ug/m^3 (14 to 32 ppm)

Values have been designated for both desirable, the goal for ambient air quality, and acceptable, that which can be tolerated for the period of time shown. These levels have been defined on the basis of effects to humans.

Carbon monoxide forms carboxyhemoglobin (COHb) in the blood and inhibits oxygen uptake in the blood. It is not known at present whether there is a threshold for adverse effects from oxygen deprivation due to COHb. Spengler and Sexton (1983) quote a study that shows that exercising adults are sensitive to COHb concentrations as low as 1%. Community air pollution and indoor exposures to combustion by-products or sidestream cigarette smoke can raise COHb in non-smokers to the 2-3% level. One symptom of CO exposures is headaches. Exposures in excess of two hours are needed before these effects are noted. At exposures in excess of 1000 ppm, severe headaches, dizziness and nauseau exist followed closely by death. If one survives an exposure in excess of 1000 ppm, long-term physiology problems remain (Henkein, 1974).

National Ambient Air Quality Standards for CO have been promulgated in the United States (45 FR 55066). These values are:

Carbon Monoxide		
United States	NAAQS	
	1 hour	25 ppm (28000 ug/m^3)
	8 hour	9 ppm (10000 ug/m^3)

The Threshold Limit Values for worker exposure to CO have been set as 50 ppm (55 mg/m^3) for the 8-hour exposure limit and the short-term exposure limit of 400 ppm (450 ug/m^3), (ACGIH, 1983).

Various other jurisdictions provide an indication of the potential range for acceptable long term CO exposure. The Federal Republic of Germany use 9 ppm. Japan sets a level of 10 ppm.

Carbon Dioxide

This simple asphyxiant serves as a potent stimulous to the respiratory system. It is both a stimulant and depressant to the central nervous system. Sources of CO_2 include combustion and the metabolism of human beings. Outdoors, the major source of CO_2 is flue gases emitted from major industrial establishments. There are no current standards for ambient levels of carbon dioxide in either Canada or the United States. Levels are generally thought to range from 0 - 400 ppm outdoors (USNRC, 1981). The carbon dioxide standards set for the workplace by the ACGIH (1983) are 5000 ppm (9000 mg/m^3) for 8 hours and 15000 ppm (27000 mg/m^3) for the short-term exposure limit.

It is interesting to note that ASHRAE (ASHRAE, 1980) has stated that acceptable levels of indoor CO_2 should not exceed 2500 ppm. Furthermore, the Ontario Ministry of Labour has noted that 8 hour exposures to concentrations of CO_2 much in excess of 800 ppm have been noted to be associated with increased complaints of "poor air" in buildings. These effects are mainly manifest in the form of headaches and an uneasy feelings about air quality in buildings. MOL are currently considering that a limit of 600 ppm CO_2 for office exposures (Pelmear, Pers. Com). It is interesting to note that the World Health Organization (WHO, 1979) recommended that the effects of low level CO_2 exposures should be re-examined.

Nitrogen Oxides

The classification nitrogen oxides (NO_x) covers a number of compounds. The main ones of concern in this particular project are NO_2 (Nitrogen dioxide), a red-brown gas that can influence visibility (smog), and NO (Nitric oxide) a compound that readily oxidizes to nitrogen dioxide. NO is the major portion of natural nitrogen oxides emissions and is

caused chiefly from bacterial action (Small, 1983). It is particularly noticeable under rainy conditions. Both NO and NO_2 are products of combustion and depending upon the type of device being used, the proportions of NO to NO_2 can change. It is noted by Ryan et al., (1983) that kerosene heaters and the like, emit substantial higher amounts of NO_2 than NO. The NO is formed by the combination of nitrogen and oxygen at the flame front but it readily oxidizes in the presence of long-chain hydrocarbons and aromatics. Conversely with lighter fuels such as natural gas, the NO will tend to dominate the combustion products. Aside from open flame burning of liquid and gaseous fuels the major sources of NO_2 are motor vehicles and industry. Oxidation of NO to NO_2 occurs in the atmosphere resulting in the levels of NO_2 being significnatly higher in the outdoor environment. In the home tobacco smoke, natural gas and other combustion operations can contribute significantly to NO_2 levels. Automobiles run in attached garages are also a significant potential source of NO_2.

Standards have been set for NO_2 exposure indoors, outdoors, and in workplaces. Only workplace standards are available for NO exposure. The ACGIH set a standard for nitric oxide (NO) of 30 mg/m^3 or 25 ppm.

Canadian Ambient Air Quality Standards for NO_2 (Canada Gazette, 1975) are noted below:

Canadian Standards, Nitrogen Dioxide

Desirable	
Annual Arithmetic Mean	0 - 60 ug/m^3 (0 - 32 ppb, 0-0.032 ppm)
Acceptable Range	
1 hour	0 - 400 ug/m^3 (0 - 213 ppb, 0-0.22 ppm)
24 hour	0 - 200 ug/m^3 (0 - 107 ppb, 0-0.11 ppm)
Annual	0-100 ug/m^3 (0-54 ppb, 0-0.054 ppm)

Small (1983) cites American standards for nitrogen dioxide exposures that have been specified in a number of locations. The US EPA quote an annual arithmetic mean of 50

ppb. California has a 1 hour average of 250 ppb. Colorado has a 1 hour average of 100 ppb. The indoor working level for NO_2 as established by the ACGIH is 6000 ug/m^3 or 3000 ppb. The World Health Organization has a 1 hour recommendation of 100 - 170 ppb (WHO, 1977). Other standards are available for locations such as Germany which complies with the range of the WHO standard and the Netherlands which specify both 1 hour and 24 hour averages combined with a frequency of occurrence. These standards state that the 1 hour average of 73 ppb is not to be exceeded during 98% of the time and the 1 hour average not be exceeded more than once per year is 160 ppb. Twenty-four hour averages are similarly stated as 65 ppb and 80 ppb. The standards are not directly comparable as they are intended for different exposures, time periods, or conditions.

The effects of nitrogen dioxide exposure are to impair lung function. The mode of action is basically inhalation into the lungs where it is converted to nitrous acid and nitric acid. These substances are irritating and corrosive to the mucous lining of the lungs. Other effects that have been noted include a reduction in sensory perception particularly with respect to the ability to distinguish odours. Increased incidence of asthma have been noted by various researchers (including Melia et al., 1977; Melia, Florey et al, 1980; and Speizer et al, 1980).

Formaldehyde (HCHO)

Formaldehyde is a ubiquitous chemical, characterized by a pungent odour detectable at levels in excess of 80 ppb. The material is present in the resins of particle board and plywood, the size used in textiles, cigarette smoke, and combustion emissions of both natural gas and automobiles. Furthermore, formaldehyde gas is noted to be released by urea formaldehyde foam insulation (UFFI) when this material degrades. While the above mentioned odour threshold for formaldehyde is recorded, it has been noted, in work recently done in Canada, that irritation of the eyes can also occur at levels somewhat below the 80 ppb.

No standards have been issued covering formaldehyde exposure in the ambient environment nor are any legislated for the indoor environment. The guidelines that are currently available include a value set by the UFFI Information and Coordination Centre to designate homes requiring remedial measures when UFFI is installed in those homes. This value has been set at 100 ppb. This is the level where remedial action is definitely

needed. The UFFI/ICC go on to state that in homes with levels in excess of 50 ppb, they will be considered for remedial measures and foam removal, if health effects are noted with people living in the homes. It should be noted that the current ACGIH TLV value is 2 ppm and the recently promulgated Ontario Ministry of Labour Standard is a ceiling limit of 1 ppm (MOL, 1983).

Health effects of formaldehyde as noted earlier include irritation of the eyes, nose, and throat and irritation of skin. Respiratory disorders including coughing, headaches, and dizziness occur in many subjects. An as yet undefined condition manifesting itself in fatigue has been noted in some residents of homes having UFFI insulation. A current epidimeological study is being undertaken by Dr. Broder at the Gage Institute in Toronto and the results of that will provide further information on the health effects of low level exposures to formaldehyde.

Radon and Radon Decay Products

Radon is a radioactive decay product of radium-226. Radium, a natural trace constitutent of rock and soil, is found in building materials made from earth crustal components. Radon-222 is a gas with a half life of 3.8 days. It decays through a series of daughter products to a relatively stable (22 year half-life) isotope, lead-210. These decay products are solid and can attach to aerosols, which may, in turn, become imbedded in the lungs and irradiate surrounding tissue. Radon gas diffuses into indoor air from the soil, building materials, water from the weeping tile around the foundations or well water. Higher concentrations are typically measured in basements, crawl spaces and in homes with low air exchange rates.

The assessment of the radiological hazard associated with a given radon concentration is complex. Daughter products can be in various states, attached to different size particles, as free ions, or as nuclei of aerosols (clouds of small fine particles). In addition, the movement of air in the area of human exposure and the length of exposure time are important considerations. For example, if there was no movement of air (stagnation) in the area of concern, radon and its daughters would be considered to be in "equilibrium". Radon concentration, therefore, would thus be a good indication of the health hazard associated with its daughters. In houses, however, this is not the case; there is always some exchange of air between the inside and outside of the house.

It is appropriate to consider the equilibrium factor as discussed above before discussing standards for homes. Radon is a gas that is 7.7 times heavier than air. It is continually emitted from all uranium or radium bearing materials. It is estimated that most of the earth's crystal material contains a concentration of uranium or radium of 1 pCi/gm and thus it is possible to estimate a global flux rate from all earth surfaces for radon of 0.5 $pCi/m^2/s$. This results in a yearly injection rate of 2.4×10^9 pCi into the earth's atmosphere. With the decay of radon gas to short lived daughters an equilibrium between the generation and decay is reached. This results in approximately 3.6×10^7 Ci existing in the earth's atmosphere at any given time (Fry, 1979). This would seem to imply that there is a potential health problem from such a radon concentration in the atmoshpere. Such a hazard has not been found to be the case, however, and radon 222 concentrations have not been successfully correlated to radiological damage data. This is attributed to the fact that the dose is largely the result of the short lived daughters of radon, particularly the alpha emitters, namely Po-218 and Po-214 which are part of the decay chain of radium. On the basis of the energies released by the decay of these two short lived daughters, a definition (WL) has been devised to help estimate the radiological response to various concentrations of radon.

The concept of the working level (WL) was developed to overcome some of the problems with the poor correlation between Rn-222 and radiological data. The basis of the definition is the potential alpha energy associated with 100 pCi of radon-222 in radioactive (secular) equilbrium with its short lived decay products. This decay energy is 1.3×10^5 MeV. If one now defines the WL as any combination of short lived decay products of radon in 1 litre of air which will result in the ultimate emission of 1.3×10^5 MeV of alpha particle energy, it is independent of the state of disequilibrium in the mixture. Since 1 WL is equal to 100 pCi/L of radon only when in secular equilbrium, it is necessary to define a relationship for the state of disequilibrium between radon and its daughters.

This equilbrium exists as the daughters move away from radon, due to ventilation of closed spaces or air movement across radon emitting surfaces. Air movement outdoors disperses the daughter products producing significantly lower concentrations of daughters. The equation defining the WL as a function of this disequilbrium is:

$$WL = F \times X / 100 \qquad \text{.....A2.1}$$

where WL = working level

F = disequilibrium factor

X = concentration (pCi/L)

F varies from 0 to less than 1 depending upon the ventilation rates.

Further to the development of F factors and WL relationships with respect to radon gas concentrations, a dose relationship must be developed based on exposure time. WL is only a concentration measurement; the dosage can be quantified by the WL month (WLM) which equals the inhalation of air at 1 WL for 1 month (170 working hours). Limits for radiation workers have been established on the basis of epidemiological data which show no excess cancers among miners exposed to 120 WLM. For a thirty year uranium miner, this equals 4 WLM/yr, the limit for industrial exposure set in several countries.

The USEPA (1980) report that, for a 0.01 WL concentration, and a lifetime exposure of 75% of the lifetime, 1% of all individuals exposed will contact fatal lung cancer over an average lifetime of 70.7 years. This means that, for persons in houses where the WL is above 0.02 (Ontario Standard), an estimated 2% will contact cancer due to radiation exposure if living in the house for 70.7 years, 18 hours/day. Some changes occur with shorter exposures but, for now, this value will suffice for considerations in this study.

The question remains then as to how one calculates the equilbrium factor, F.

The decay chain referred to earlier is shown in schematic form in Table A2.1. This table shows not only the radionuclide, its half life, decay constants, and potential energies, but also the conversion factor between energy and working levels in pCi/L. As decay of radon-222 occurs the concentration decreases in the atmosphere. This decrease also occurs due to dilution with fresh air coming into a building, particle settling or particle absorption to surfaces. Kusuda et al (1980) presents a series of equations which characterize radioactive decay and convective dilution in a building. The basis of these equations are shown below.

TABLE A2.1: POTENTIAL ALPHA ENERGY OF ^{222}Rn AND ITS SHORT-LIVED DECAY PRODUCTS[9]

Radionuclide	i	Radioactive half-life	Radioactive decay constant (min^{-1})	Number of atoms/ picocurie	Potential alpha energy (MeV) Per atom	Per picocurie	Conversion factor Ci $MeV.L^{-1}$ / $pCi.L^{-1}$	WL / $pCi.L^{-1}$
^{226}Ra								
^{222}Rn	0	3.8 days	1.258×10^{-4}	17488				
^{218}Po(RaA)	1	3.05 minutes	0.2272	9.77	13.68	134	134	0.00103
^{214}Pb(RaB	2	26.8 minutes	0.02586	85.3	7.68	659	659	0.00507
^{214}Bi(RaC)	3	19.7 minutes	0.03518	63.1	7.68	485	485	0.00373
^{214}Po(RaC')	4	1.6×10^{-4} seconds	3.75×10^{-5}	10^{-5}	7.68	7.68×10^{-5}	7.68×10^{-5}	6×10^{-10}
^{210}Pb								

Taken from Kusuda (1980)

$$\frac{dA_o}{dt} = Q - (\lambda_o + I) A_o + IA_o^o \qquad \text{.....A2.2}$$

$$\frac{dA_i}{dt} = \lambda_i A_{i-1} - (\lambda_i + I) A_i + IA_i^o \qquad \text{.....A2.3}$$

for $1 \leq i \leq 4$

where i = 0 through 4 denotes the parent radon and the 4 decay daughters in the chain,

A_i = the activity concentration of the i^{th} radionuclide (pCi/L) at time t,

λ_i = its decay constant (minutes to the -1),

I = the air exchange rate (minutes to the -1),

Q = the source strength, the entry rate of radon-222 into the building per unit volume (pCi/L.min), and the absence of a superscript refers to indoor values while the ^{o} refers to outdoor values.

The most difficult value to characterize in these equations is Q, the source strength. As discussed above, it depends upon the types of construction materials used, the sources of water, the ground over which the building is erected and possibly atmospheric conditions.

Using equations A2.2 and A2.3 to define the activity concentration, allows one to define the energy available from the various radionuclides using:

$$E = \sum_{i=1}^{4} C_i A_i \qquad \text{.....A2.4}$$

where C_i is equal to the coefficients shown in Table A2.1.

These coefficients represent potential alpha energy per pCi of each of the daughters. With this definition it is now possible to define the energy available at radioactive

equilibrium. Since the concentration at equilibrium of each of the daughters will be approximately equal, the equilibrium concentration can be defined by:

$$E = \sum_{i=1}^{4} C_i A_o = \frac{A_o}{100\ pCi/L}\ WL \qquad .....A2.5$$

This now provides a definition on which to calculate the equilibrium factor (F). The ratio of E/E is the measure of the deviation from equilibrium of radon and its daughter concentrations. This is defined by:

$$F = \frac{E}{\overline{E}} = \frac{((100\ pCi/L)/(WL)) \sum_{i=1}^{4} C_i A_i)}{A_o} \qquad .....A2.6$$

The equilibrium factor can now be used to define the potential of energy concentration given a radon activity.

Kusuda and his co-authors go on to solve these equations in their paper and two of their main conclusions are of importance to this study. The authors provide a plot of potential alpha activity vs. time for various air exchange rates in the model house. These calculations are based on no outdoor radon activity. The calculations show that equilibrium is not quite reached even after two weeks with the extreme case of no air exchange rate. Very slight changes in the air exchange rates from zero to 0.05 ACH produce a radon removal rate of 7.6 times greater than the zero exchange rate. A further minute increase from 0.05 to 0.1 ACH nearly doubles the radon removal rate. The implications of this finding are that there will be a great deal of data scatter in any measured values in actual houses since the air exchange rate will vary with wind speed, temperature, opening of doors, windows, operation of fans or furnaces and the like. This implies that it will be difficult to correlate measured radon and radon daughter concentrations with standards or other studies if the homes do indeed have the low infiltration rates measured.

The authors (Kusuda et al, 1980) further show the effect of the various air exchange rates on the equilibrium factors. They show that the equilibrium factor varies inversely with air exchange rates at steady states, and increases from 0.61 at 1 ACH to 0.73 at 0.5 ACH and 0.86 at 0.2 ACH. The data goes on to show that there is no clear relationship between the disequilibrium factor and the air exchange rate during the first two hours of any period. This implies that it will be difficult to predict, on theoretical grounds, the value of the disequilibrium factor in actual buildings.

To date most models that have been used to calculate working levels in homes have undertaken this work on the basis of steady state air exchange rates. Commonly, in the uranium industry mines and mills, steady state air exchange rates can be determined as the ventilation systems run continuously. The situation in a residential home is, however, significantly different. People may open and close windows and doors, furnaces will run intermittently, and people will stop and start ventilation fans depending upon their needs. Clearly, a steady state condition is not reached in the houses and thus some difficulties arise in defining adequate equilibrium levels for homes. This implies that there will therefore be some difficulties in developing criteria to assess the levels of radon and its daughter products in homes and the consequential radiological implications.

While limits have been set for radon daughter exposures in the working environment, the most important criteria for the purposes of this report are those developed by the Atomic Energy Control Board (AECB, 1977). In this document they designate a primary clean-up criterion for radon daughter products as 0.02 WL. The health risk resulting from continuous exposure to 0.02 WL is comparable to the risk associated with the radiation dose limits specified in the Atomic Energy Control Regulations for persons living in the neighbourhood of licenced nuclear facilities. These specified dose limits for members of the public are 1/10 of the limit for persons exposed to radiation in the course of their work.

The AECB (1977) go on to state that three levels can be used to screen buildings intended for application as actual and potential living space (homes) or occupied space in other buildings. They apply these levels to the average radon and daughter concentration over the course of one year. It should be realized that short-term fluctuations above the quoted values are not signficant as long as the yearly average meets the clean-up criterion. The three levels specified for radon and radon daughter levels inside buildings are as follows:

- o prompt interim action - greater than 0.15 WL
- o primary criterion - greater than 0.02 WL
- o investigative level - greater than 0.01 WL.

Based on data commonly available, an equilibrium factor of 0.3 was selected by the AECB (1977) for use in for normal houses. Using this factor they calculate the radon concentration corresponding to the above mentioned levels. These are respectively 50 pCi/L, 7 pCi/L and 3 pCi/L. Note should be made though of the potential inadequacy of such a conversion procedure if it is used for calculations in well sealed homes.

The effect of the exposure to high radon levels is not manifest quickly. The pollutant is a long-term problem as far as health effects are concerned. The results of radon levels being too high and the subsequent inhalation of the gas, is the promotion of lung cancers.

A2.2 Typical Environmental Levels

Common values of indoor and outdoor pollutant concentrations are quoted extensively in literature. Rather than trying to present all of the information that is available, the following presents a summary based on the work of Small (1983) and other recent references.

Carbon Monoxide

The primary source of outdoor carbon monoxide measurements in Canada is the National Air Pollution Surveillance program. This program is run by the federal government to assess ambient air quality concentration levels in major urban centres in the country. Strictly speaking, interpretation of these data to a specific site is not possible since readings are highly correlated with local activities. Carbon monoxide is generated by automobile exhausts implying that, in areas of high traffic volume, one would find higher CO levels. In a summary of air quality trends in Canada (Barton, 1981) it is reported that the annual mean for carbon monoxide in urban centres in Canada for 1979 was 1.7 ppm. Sixty-three percent of the stations in that particular study had eight hour averages between 5.1 and 13 ppm with 18% of the stations having eight hour averages of less than 5.1 ppm. One hour averages of CO recorded in the same study indicate that 39% of these stations had values less than 13 ppm and 55% had one hour values between 13.1 and 31

ppm. Generally speaking, one would anticipate that levels of outdoor CO concentrations in Cambridge would probably be below the values quoted above.

Information on indoor levels are not as readily available as outdoor levels. Being closely related to the type of activities in the house, there is a wide variance in these values. A number of different studies can be quoted to provide some idea of what typical indoor levels could be. Yocom et al., (1970) report indoor levels varying from 0.5 to 5 ppm as an average, with peak values as high as 100 ppm. Sterling et al., (1981) report that indoor levels are between 6 and 7 ppm near medium sized thoroughfares. Sterling and Sterling (1979) report values in kitchens with gas ranges to be between 34.5 and 120 ppm when averaged over 20 minutes. These values closely relate to those reported by Hollowell and Traynor (1978) who reported that ovens operated for one hour at 180°C resulted in concentrations in the kitchen of 50 ppm and if the air change rate in the house dropped below 0.24 ACH the level exceeded 50 ppm. At one air change per hour these levels were reported to be below 35 ppm. Brookman and Birenzvige (1980) noted that one could find a variation between different rooms in a house of up to two times. Recent data on kerosene heaters shows that these devices can be very detrimental to indoor air quality particularly with respect to carbon monoxide and nitrogen oxides. (Ryan et al., 1983; Traynor et al., 1983).

Carbon Dioxide

As quoted previously, the USNRC (1981) state that indoor levels of carbon dioxide can range from 0 - 3000 ppm where outdoor levels are 0 - 400 ppm. Little other data is found in the literature, possibly due to the fact that CO_2 is a product of the natural metabolism of humans.

Nitrogen Oxides

Values for the concentration of nitric oxide (NO) inside homes are generally reported to be in the range of 30 - 300 ppb with maximum levels as high as 500 ppb (Small, 1983). Outdoor values for nitric oxide are not routinely measured, but Robinson (1970) reports non-urban levels to average 2 ppb.

The standard ambient NO_x measurement device measures total nitrogen oxides (NO_x) and

reports the values expressed as NO_2. These NO_2 values are monitored in locations similar to those discussed previously for carbon monoxide. The annual mean values for all stations in 1979 are approximately 260 ppb (Barton, 1981). Ninety-two percent of the stations in Canada report a 24-hour maximum average between 0 and 110 ppb with the balance of the stations being below 160 ppb. One hour maximum values of 210 ppb were recorded at 96% of the stations. Values below 530 ppb for one hour averages were recorded at 98% of the stations with the balance of the stations reporting a one hour maximum in excess of 530 ppb. Again, caution should be used in interpreting these data since siting criteria for monitors is heavily related to vehicular traffic, a major source of NO_2.

Nitrogen dioxide values indoors are generally reported in the range of 100 - 530 ppb (USNRC, 1981). Hourly fluctuations have been noted to be between 50 and 500 ppb with peak values of 700 ppb. Weekly average NO_2 values range from 20 to 100 ppb.

Indoor data reported by Hollowell and Traynor (1978) shows that gas stoves with one burner on for 30 minutes can produce indoor levels of 540 ppb. The oven operating for 20 minutes can produce 900 ppb. At 2 1/2 air changes per hour, values in excess of 400 ppb were recorded by these researchers for ovens set at 350°F. Speizer et al., (1980) report similar values of indoor NO_2 levels. Long-term sampling by these researchers showed geometric means of between 8 and 30 ppb in homes with gas stoves and 2 to 23 ppb in homes with electric stoves. Lebret et al., (1981) undertook some long-term (weekly) studies which produced average values in the range of 65 ppb. The overall range of the samples studies though was from 20 to 250 ppb with gas fired ranges. In the previously quoted study by Melia and Florey et al. (1980), they measured NO_2 levels in houses equipped with gas ranges and electric ranges. For the purposes of comparison of health effects, they took average concentration values inside both types of houses and outside. The results showed that in those houses with gas ranges the levels ranged from 5 to 317 ppb with an average of 112 ppb NO_2. For those homes with electric ranges the values ranged from 6 to 118 ppb with an average of 18 ppb. These values were recorded in areas with outdoor concentrations ranging from 14 to 24 ppb and averaging 18.5. Further studies by these researchers showed that values in other rooms of these homes, namely bedrooms, revealed average values of 30.5 ppb in bedrooms of homes with gas ranges and 13.9 ppb in bedrooms of homes with electric ranges.

Formaldehyde

Commonly accepted outdoor levels of formaldehyde range from 10 to 50 ppb. Formaldehyde testing reported by numerous researchers tend to confirm these values. Testing at busy intersections during rush hour in London, Ontario revealed values in this range (UWO, 1983).

Indoor values for formaldehyde range from 10 to 1000 ppb depending upon numerous factors. A great deal of measurement sponsored by UFFI/ICC has shown that values in homes with UFFI can range from 20 ppb to in excess of 1000 ppb. Homes without UFFI have recorded values ranging anywhere from 10 ppb to 90 ppb, however, in the cases of high readings, there is usually new particle board construction or occupant smoking.

Radon

Radon concentrations outdoors are highly dependent upon local sources. These values tend to be reported in terms of pCi/m^3 as opposed to the working level or pCi/L values quoted earlier. The generally accepted normal background values for Radon-222 in the atmosphere range from 100 to 1000 pCi/m^3 (0.1-1.0 pCi/L).

McGregor et al., (1979) report on the measurement of radon and radon daughters carried out in 14 Canadian cities and 9,999 homes. The geometric means of the different cities varied from 0.14 to 0.88 pCi/L for radon gas and 0.0009 to 0.0036 working levels for radon daughters. It was concluded from that study that the radon originated from natural radioactive in soils surrounding the homes. Other data is presented by Oswald et al., (1982). These researchers report that indoor values of radon gas range from 0.1 to 1140 pCi/L depending upon location and season. In a report prepared for the Canadian AECB (DSMA ATCON, 1980) survey results were presented for 248 houses located in Elliot Lake, Ontario. These houses were located in areas where mine tailings had been used as aggregate fill. Based on a derived remedial action criterion of 5 pCi/L, the average radon concentration in 218 homes was identified as being below the criterion, 24 were above the criteria and the remaining 6 were close to the criteria.

A2.3 Indoor/Outdoor Air Quality Relationships

A critical review on this subject was prepared by Yocom (1982) for presentation at the annual Air Pollution Control Association meeting in 1982. This report brings together extensive experimental data collected on indoor/outdoor air quality relationships and summarizes much of the currently available information.

Since most people spend a large part of their time indoors, it is important to consider the levels that can arise in that environment. Traditionally, air quality standards have been set on the previously discussed outdoor measurements. At best, monitoring of outdoor air quality provides an indication of localized ambient air quality and is not applicable to the wide ranges of residences in typical urban areas. As discussed earlier, the Canadian NAPS program measures ambient air quality levels in some urban environments in Canada, but no data are available for the Cambridge area. Some data were collected on outdoor air quality levels in this study and, therefore, comparisons can be made between indoor and outdoor levels for this study. To put any comparison values into context, it is worth using the data generated by Yocom (1982) as a reference point for any discussion of indoor/outdoor air quality ratios.

Carbon Monoxide

In the absence of sources indoors, the carbon monoxide levels generally mirror the outdoor values. Should indoor sources, such as those mentioned previously, occur, indoor levels have been noted to be between 1.2 and 3.8 times the outdoor values.

Nitrogen Oxides

As a general value, the ratio of nitrogen oxides indoors to outdoors has been shown to be 1.12 for houses equipped with gas stoves and 0.38 for residences equipped with electric stoves. Interestingly enough, office buildings record an indoor/outdoor ratio of NO_2 of approximately 0.84. No explanation of a higher level recorded in office buildings is provided in Yocom's work, however, it can be postulated that smoking may contribute to higher NO_2 levels in office buildings. When comparing indoor/outdoor ratios in homes with gas stoves and without, it is shown that smoking has a very small contribution to the overall ratio compared with the contribution of gas stoves.

Only limited work has been done on the ratio of NO_2 to NO. This work has chiefly been related to the potential for gas-fired appliances to generate nitric oxide. The data available show that the ratio of NO_2 to NO can range from 0.48 to 0.8 for range burners, 1.2 to 3.96 NO/NO_2 for pilot lights, and 1.48 to 1.51 NO_2/NO for ovens. No data are actually available on indoor/outdoor ratios of NO.

In summary, the indoor/outdoor ratio for NO_2 tends to be significantly less than one if there are no sources in the home, it can range as high as 5 in the kitchen of homes with gas stoves and decreases somewhat in other areas of the house. The NO_2 levels are maintained in the house for periods between one-half and three-quarters of an hour if there is no air exchange in the house. This time represents the time for the initial concentration in the house to decrease to half the initial level.

Carbon Dioxide

Carbon dioxide concentrations are chiefly based on the occupancy density of the building and the use of unvented appliances in the building. Yocom reports two studies: one by GEOMET which reported indoor levels from 150 to 2,200 ppm and outdoor levels of 100 to 500 ppm. A similar study conducted by EPRI quoted indoor values of 300 to 2,385 ppm against outdoor values of 260 to 766 ppm. Calculated indoor/outdoor ratios for CO_2 are presented by Yocom for an LBL study. These indicate ranges from 2.3 - 4.0 for the I/O ratio.

Formaldehyde (HCHO)

Formaldehyde, and radon which will be considered later, are two pollutants which, while they may have outdoor sources, have a major impact on the indoor environment. The presentation of indoor/outdoor ratios of these pollutants is not necessarily appropriate given the fact that the major sources tend to be in the home.

Yocom reports indoor/outdoor rates for formaldehyde in two energy-efficient homes, one of which showed a value greater than 4.7 and one where the value was greater than 10.

Radon

Radon tends to be an indoor air quality problem. The data available shows that levels outdoors are strongly correlated with the local geology. One cannot, therefore, generalize about indoor/outdoor levels. As discussed previously, another complication arises when attempting to correlate radon levels with the effect on humans, since radioactive radon daughters require consideration. The data presented in the previous section of this chapter shows that normal background values for radon-222 gas in the atmosphere range from 0.1 to 1 pCi/L. An extensive amount of data are reported in the previous section and shows values indoors range from 0.1 to 1,140 pCi/L. Clearly, the application of an indoor/outdoor ratio to radon is inappropriate.